Utilization of Modeling and Simulation in Lower Extremity Injury Analysis

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Jeffrey S. Augenstein, MD, PhD
University of Miami
Kennerly Digges, PhD
George Washington University

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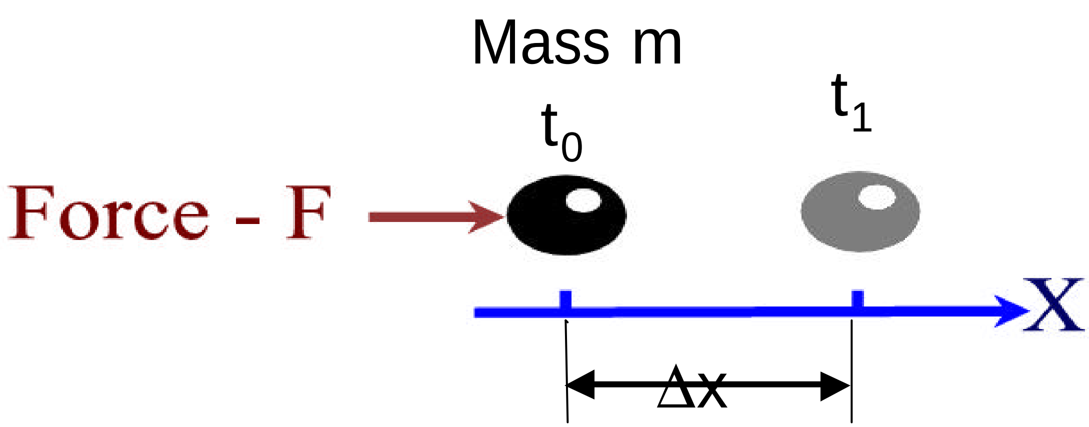
Outline

- Lump Mass Modeling 101
- Data Sources
- Upper Leg Injury – Case Study
- Lower Leg Injury – Case Study

Lumped Mass Modeling 101

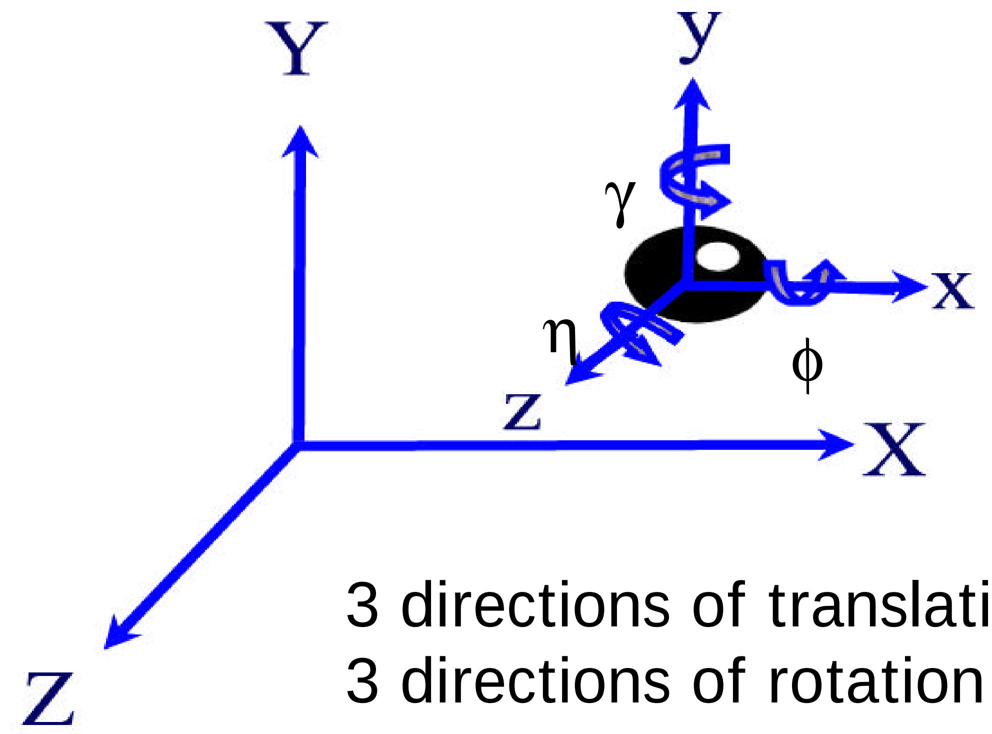


$\Delta v = a \times \Delta t$

$\Delta x = ½\, \Delta v \times \Delta t = ½\, a\, \Delta t^2$

$a = F/m; \quad \Delta x = ½\, F/m\, \Delta t^2$

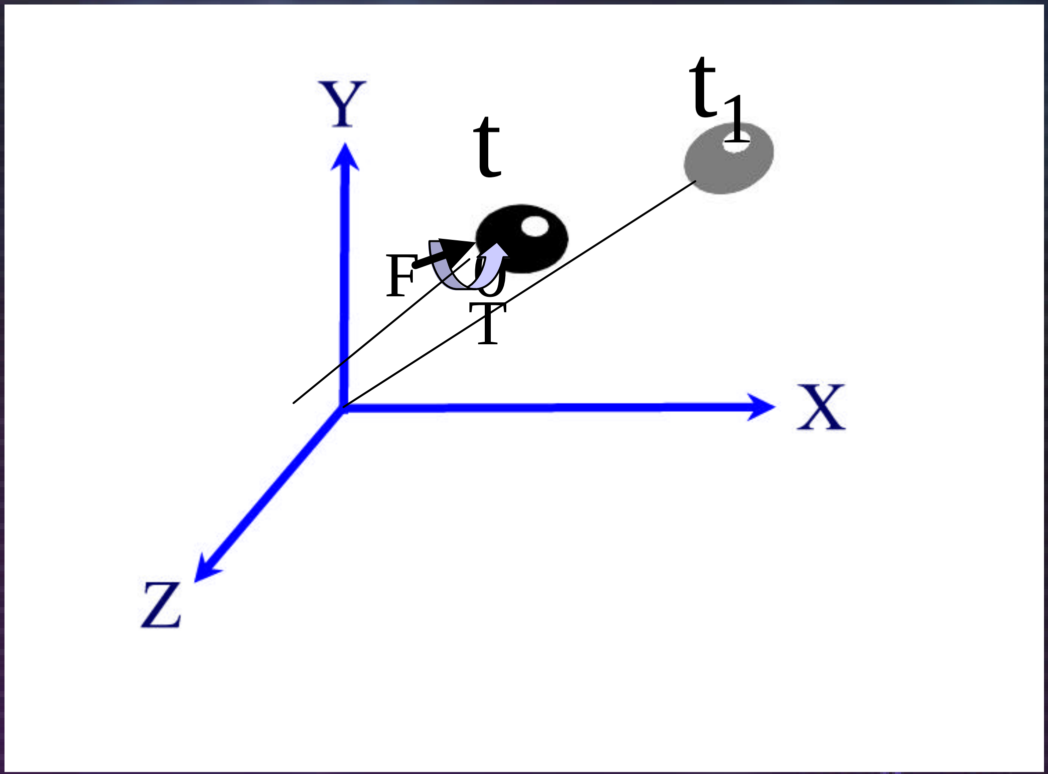
Degrees of Motion for Models



3 directions of translation, x, y, z

3 directions of rotation, ϕ, γ, η

Lumped Mass Modeling Approach



Apply single degree relationships to:

X, Y, Z for Linear Displacements

ϕ, γ, η for Angular Displacements

Forces Are Not Constant With Displacement

Modeling Requires Force Vs. Displacement Relationships

- Force = K (x) Hook's Law
- Torque = k r(ϕ)

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Modeling Requires More Than One Mass

- Add masses connected by joints
- Add geometric compatibility relationships

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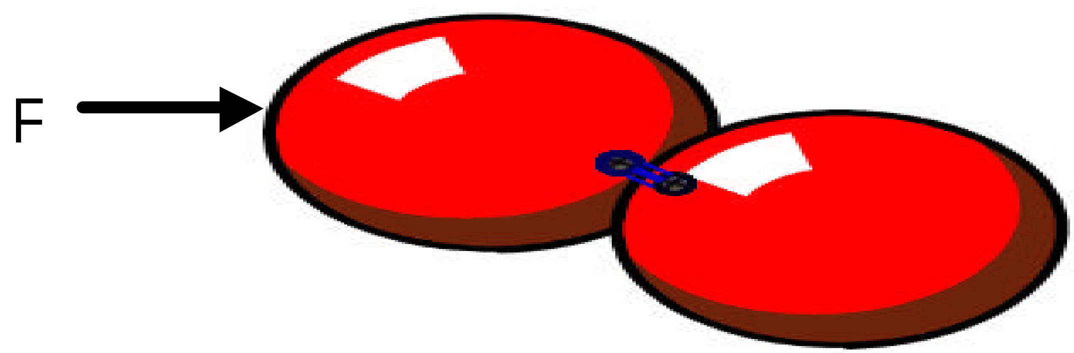
Add Lumped Masses Connected by Joints

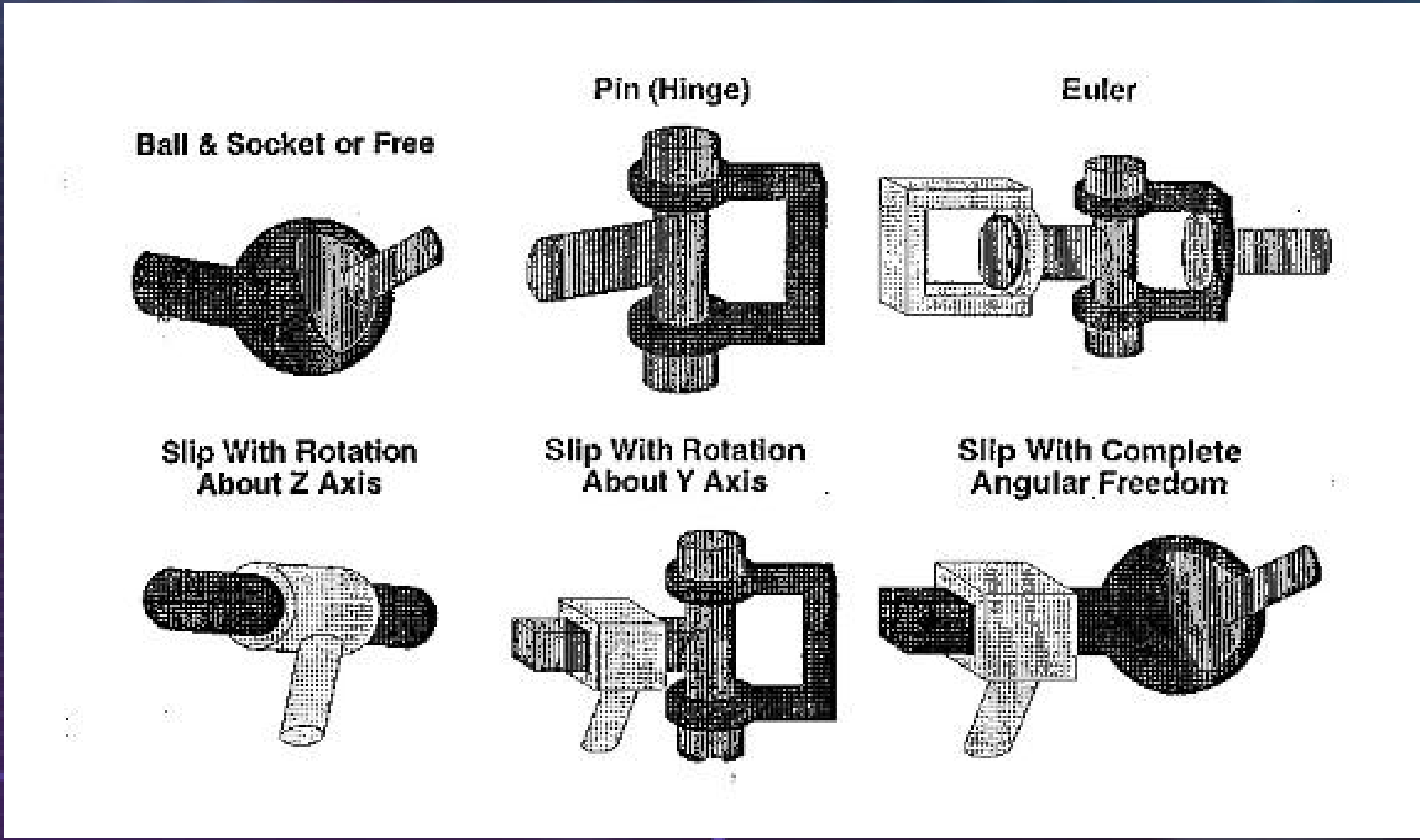
Applicable Laws and Principles:

- Newton's 1st Law; $F = ma$; $T = I\alpha$
- Force & Torque Equilibrium; $\Sigma F = 0$; $\Sigma T = 0$
- Force vs Displacement Relationships
- Geometric Compatibility; Joint Constraints

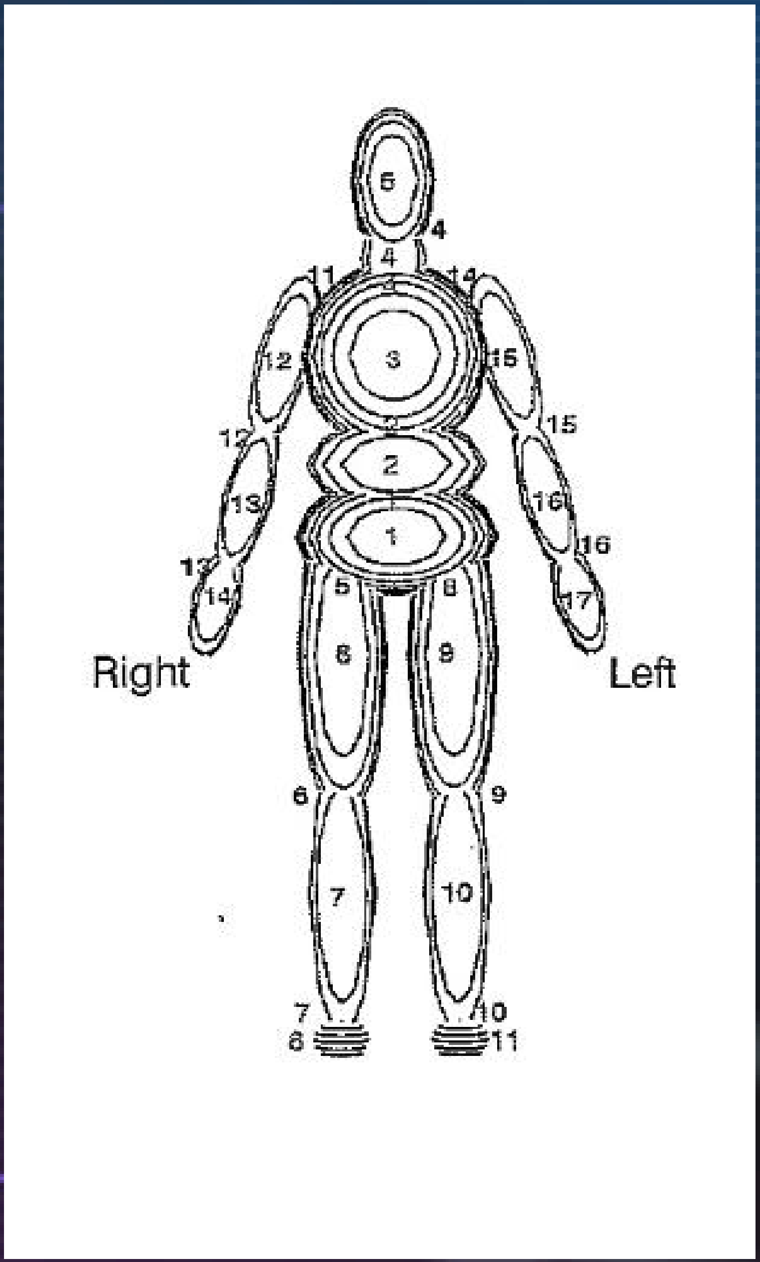
Two Segments Connected by a Joint



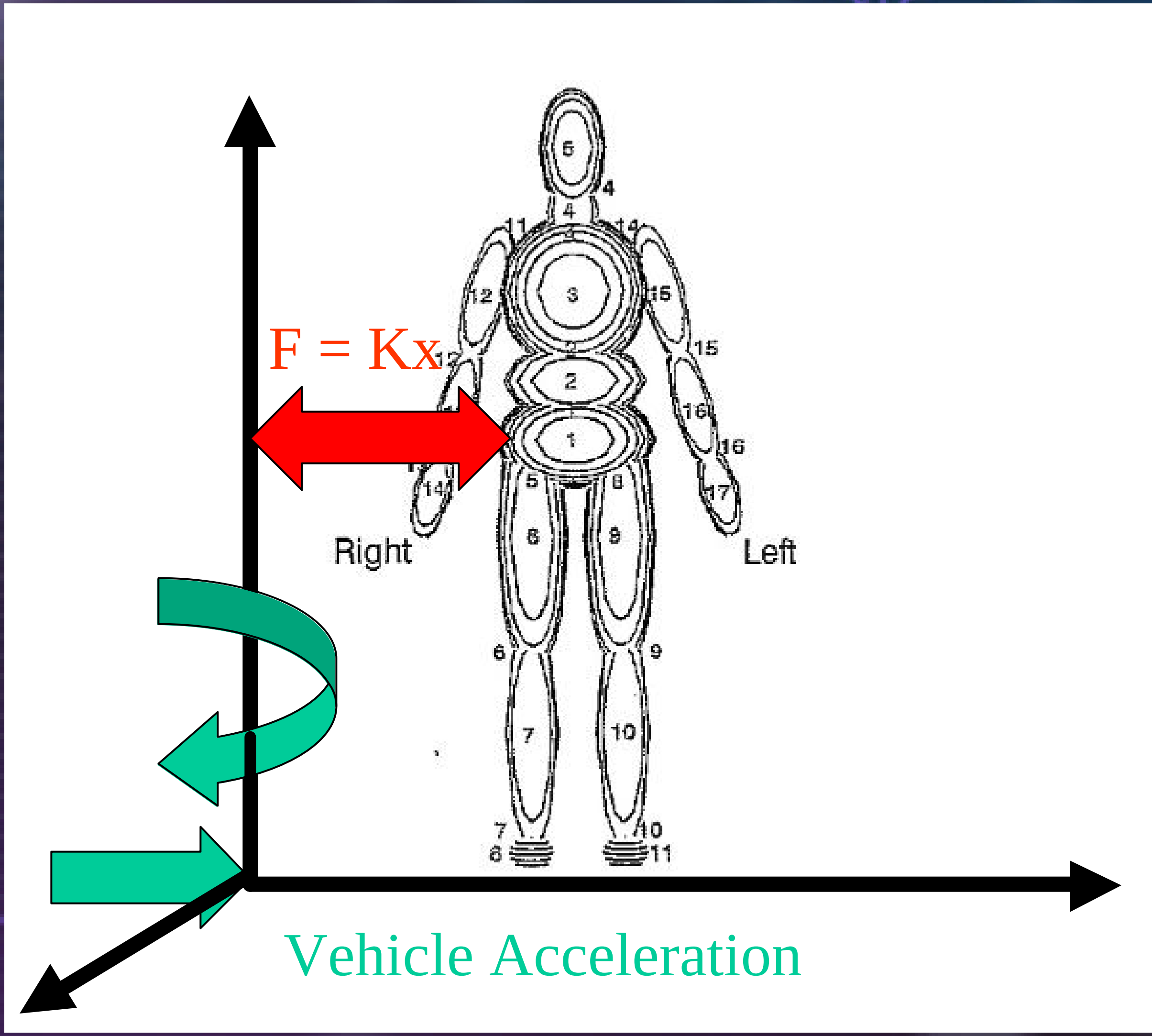
Typical Joints for Modeling



Hybrid III
Dummy Model
17 Masses &
16 Joints



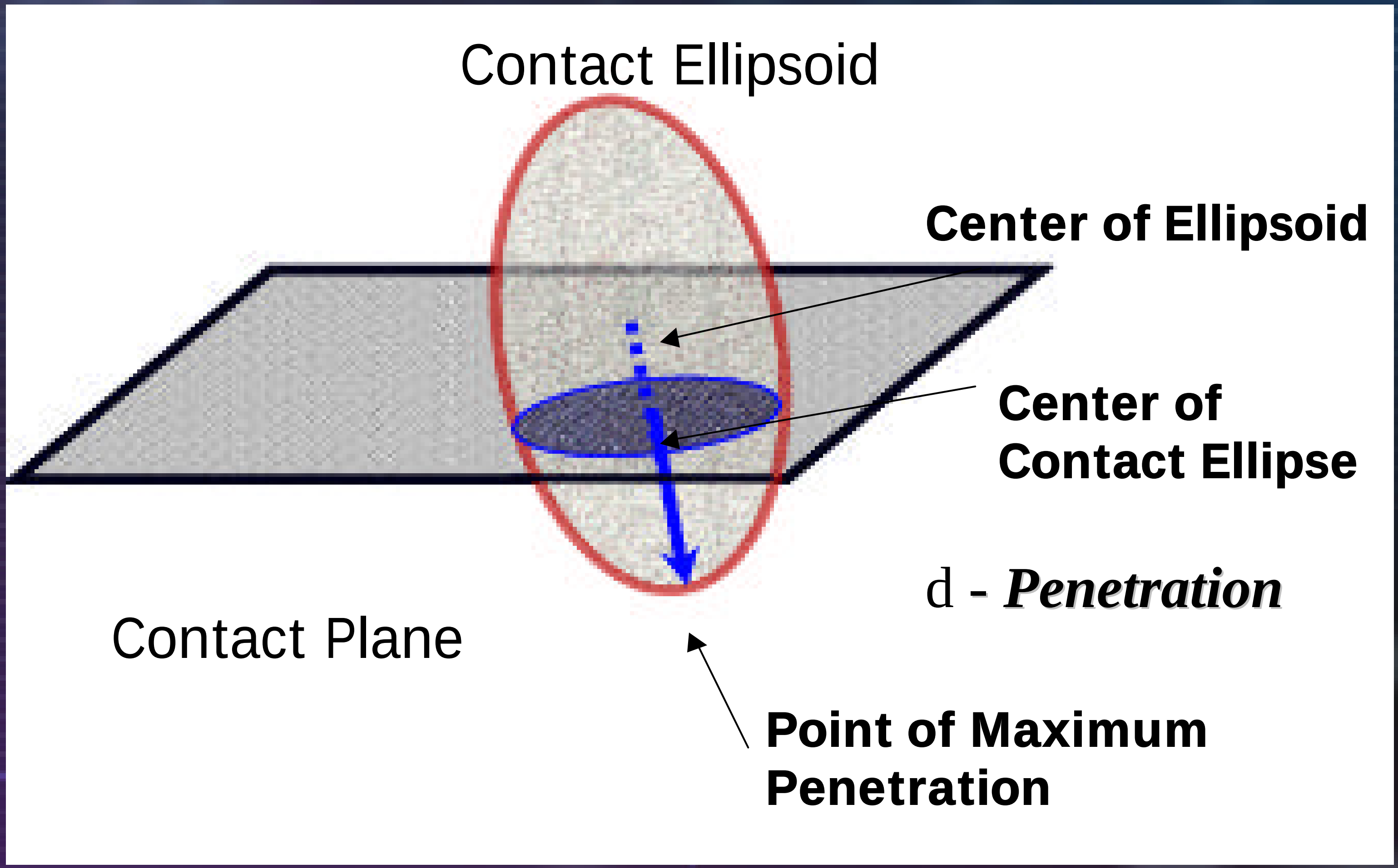
Input - Vehicle Acceleration vs Time & Force Displacement Relationships



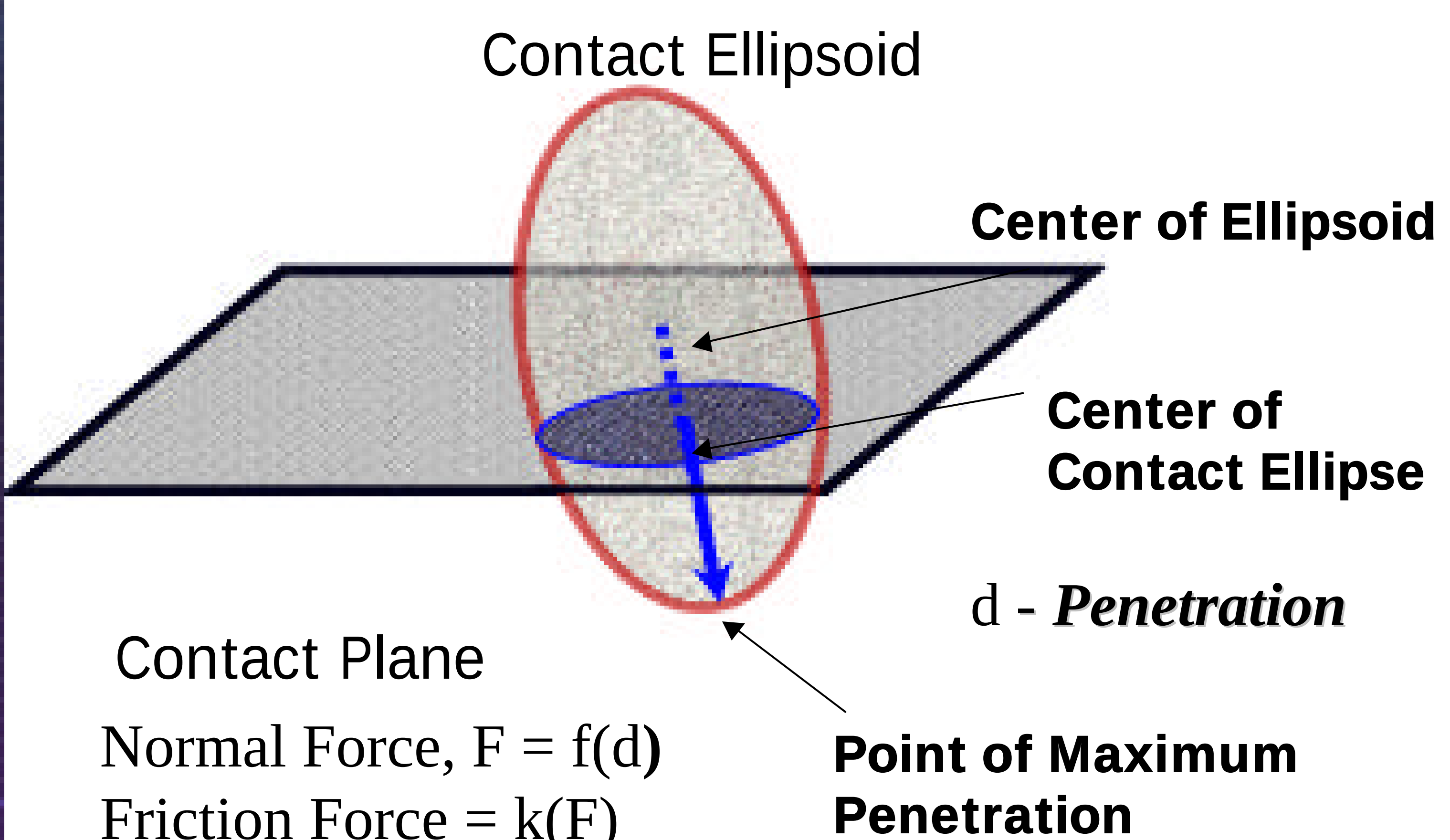
Force Displacement Relationships

- Body segment surfaces represented by ellipsoids
- Vehicle surfaces represented by either:
  - Planes
  - Ellipsoids
  - Hyper-ellipsoids
- Contact forces represented by penetration of vehicle surfaces by body ellipsoids

Definition of Penetration



Definition of Penetration

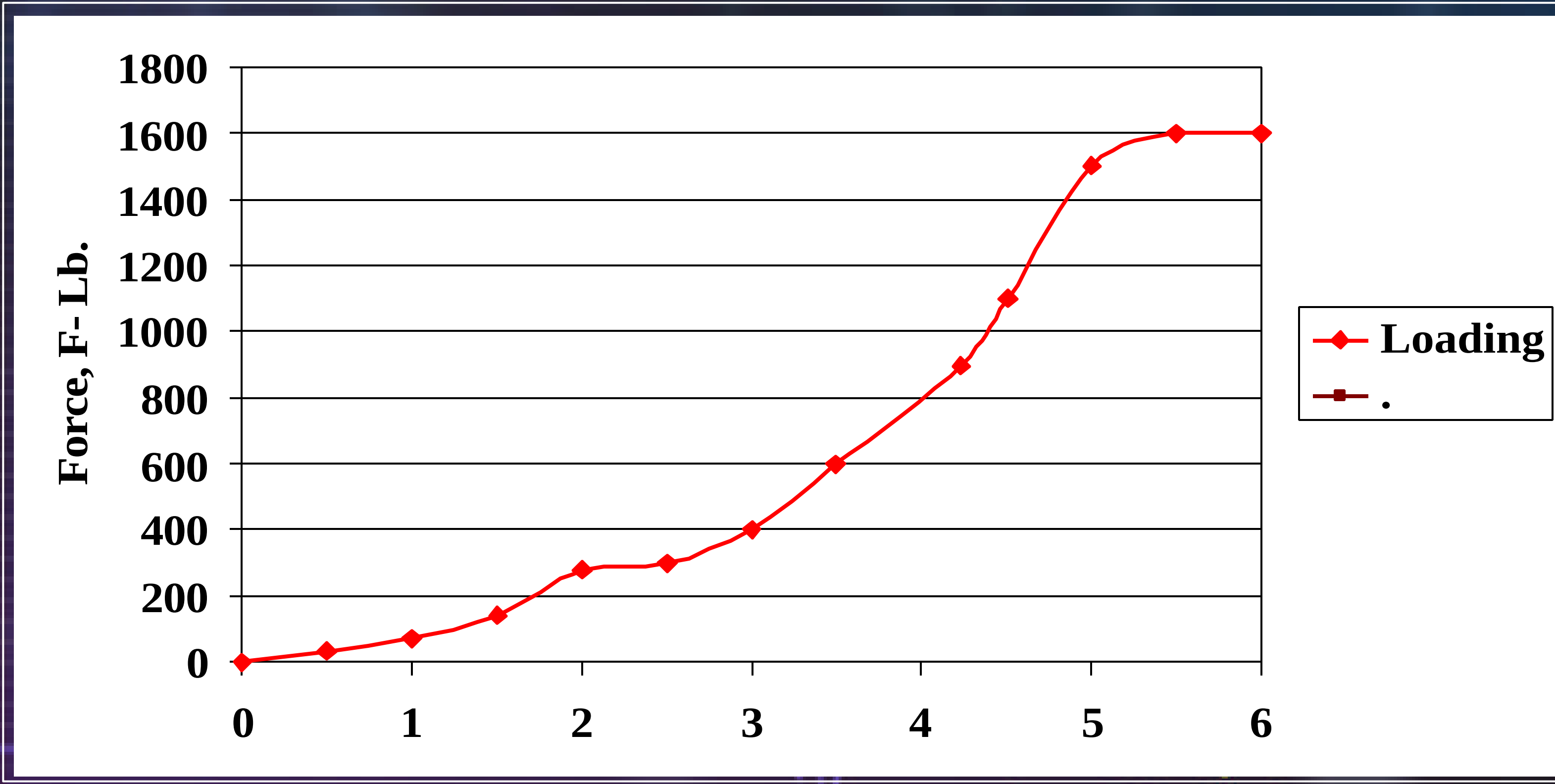


Normal Force, F = f(d)

Friction Force = k(F)

Typical Penetration vs. Force Relationship

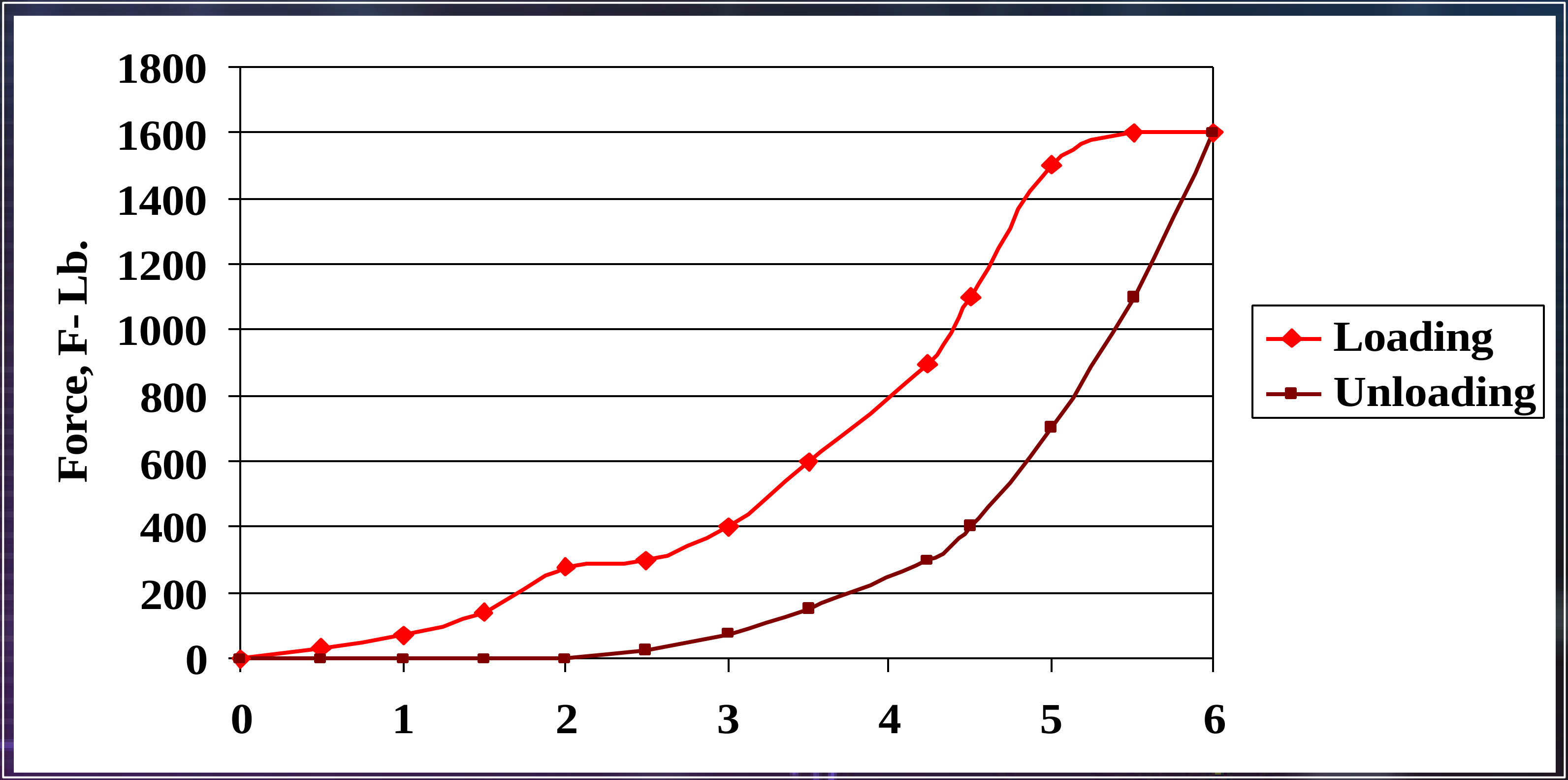
Penetration, δ - in.



Deformation, in.

Typical Penetration vs. Force Relationship

Penetration, δ - in.



Deformation, in.

Computer Reconstruction of Crashes

Alternative Models

Input Data

Sources of Data

Injury Criteria

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- ATB - lumped mass with string belts
- MADYMO - lumped mass with FEM belts & contacts
- LSDYNA - finite element with rigid skeleton

Comparison of Models

MODEL	COMPUTER	TIME
ATB	PC	30 sec
MADYMO	WORKSTATION	15 min
LSDYNA	POWER CHALLANGE	3-12 hrs

Approach to Reconstruction

- Use lumped mass models to gain insight into injury mechanisms
- Use cadaver tolerance data to interpret model predictions
- Use FEM models to study injury sensitivity of crash parameters to loads at locations where injury occurs

Input Data Needs for Crash Reconstruction

- Occupant Model
- Vehicle Interior Geometry
- Force Deformation, Friction and Hysteresis of Belts, Air Bag, and Other Contacts
- Crash Pulse (and Intrusion Time - Displacement)
- Initial Position of Occupant

Input Data Needs for Crash Reconstruction

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Occupant Model

- Validated models of hybrid III dummy available
- Scaling programs available for different size occupants
- No validated human model available
- Simulation is of a dummy not a human!

Input Data Needs for Crash Reconstruction

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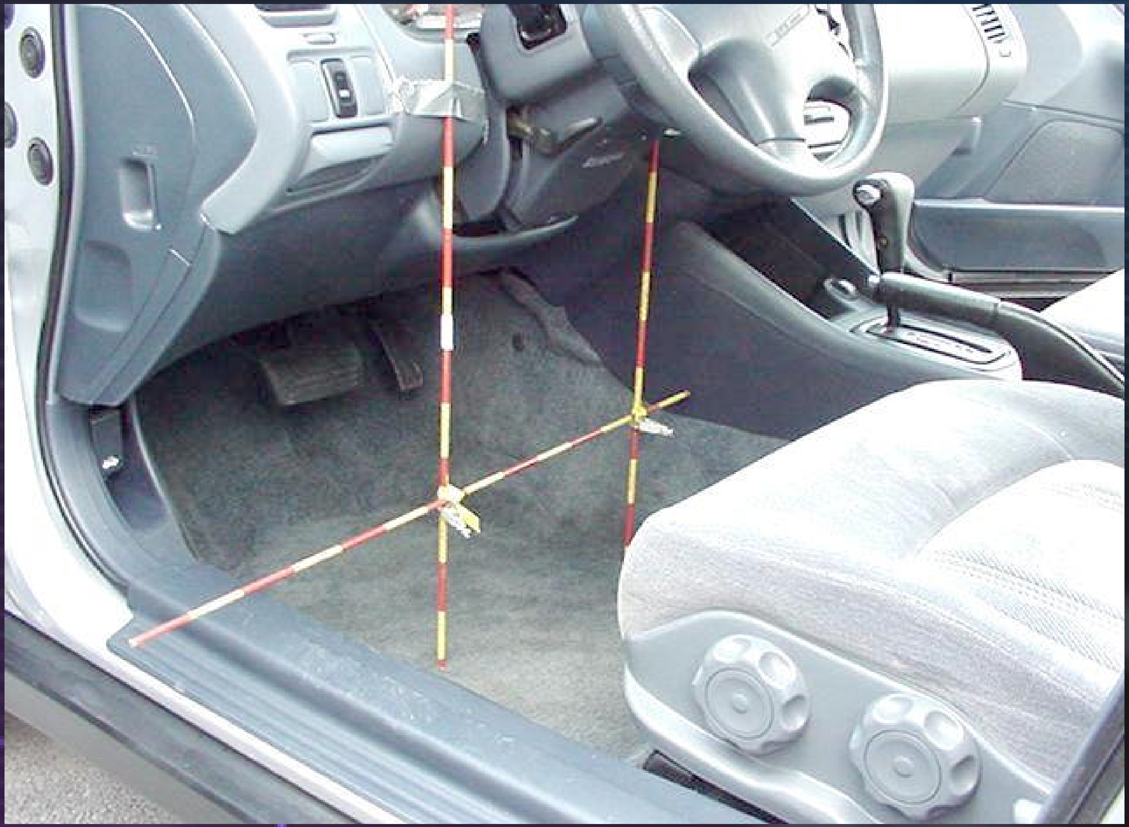
Vehicle Interior Geometry

- Obtained by Direct Measurement



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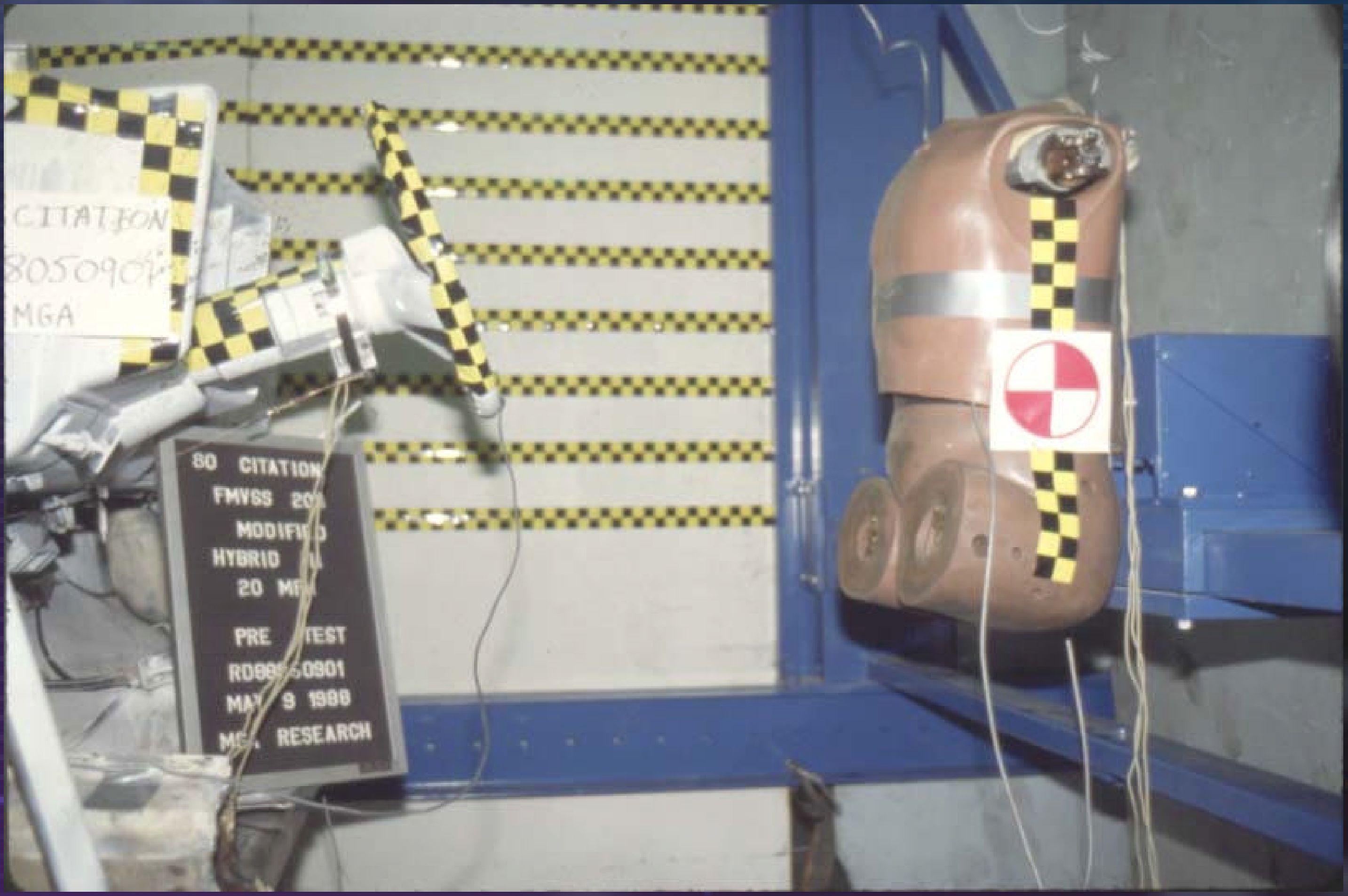
Force Deformation Properties

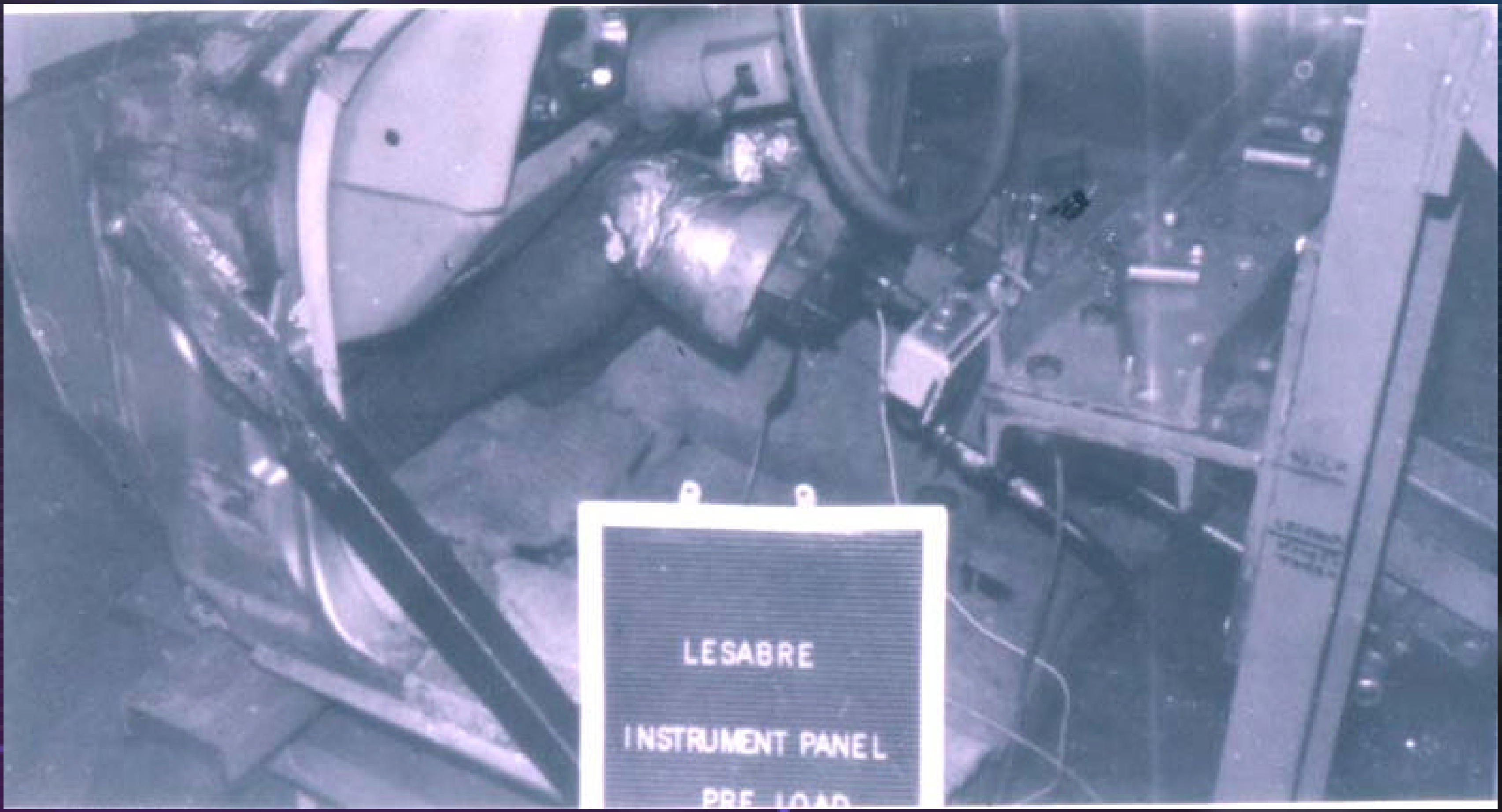
- Library of properties available from NHTSA research testing

- NCAP and compliance tests of vehicles used to “tune” properties of knee restraints, air bags, and belts

NHTSA Steering Column Dynamic Test



NHTSA Knee Restraint Static Test



Input Data Needs for Crash Reconstruction

- Occupant Model
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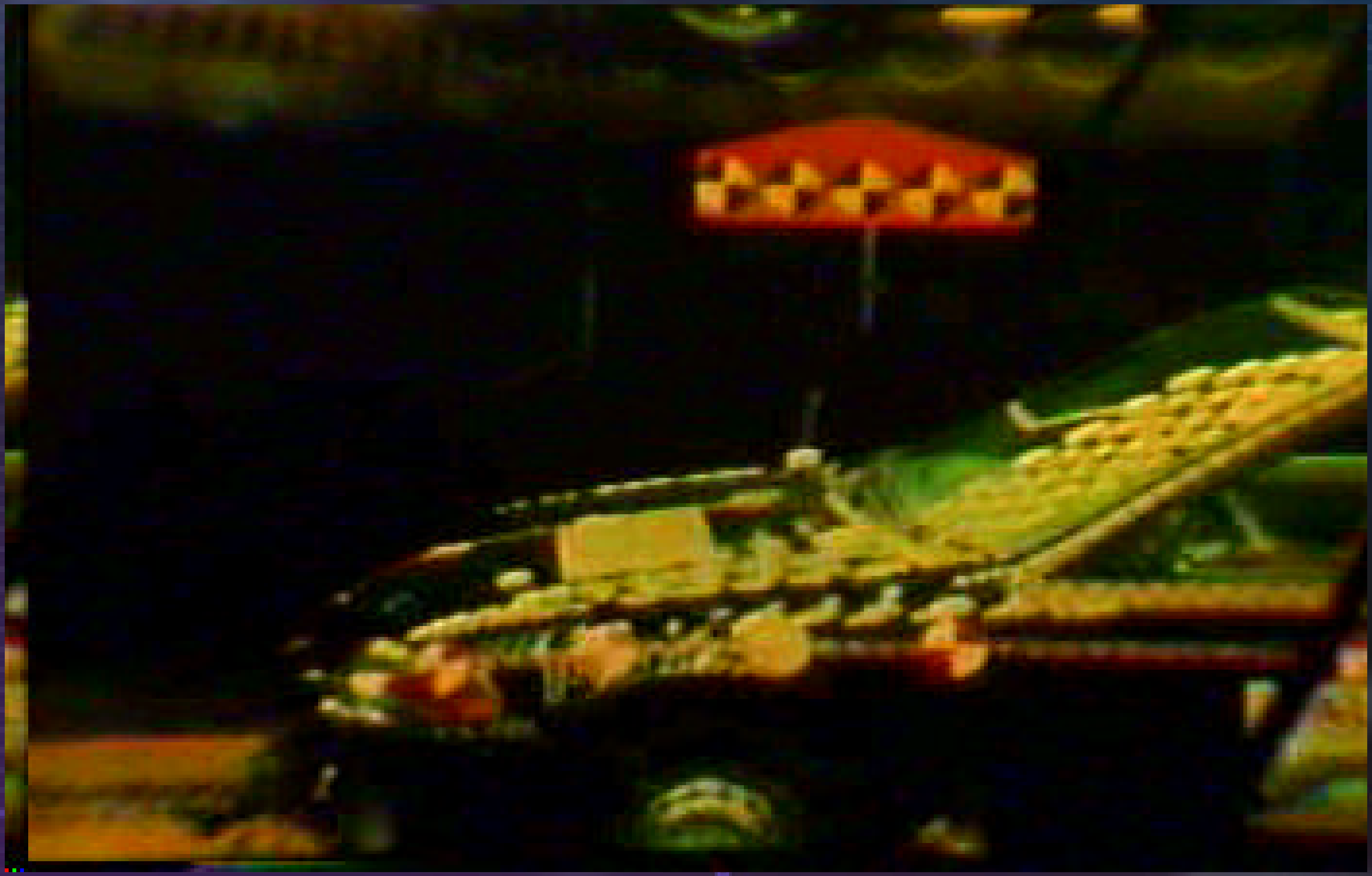
- Initial Position of Occupant

NCAP and Compliance Tests

- Crash pulse
- Belt slack
- Intrusion history
- Belt and air bag response
- Knee restraint response

NCAP - 35 mph

See Movie

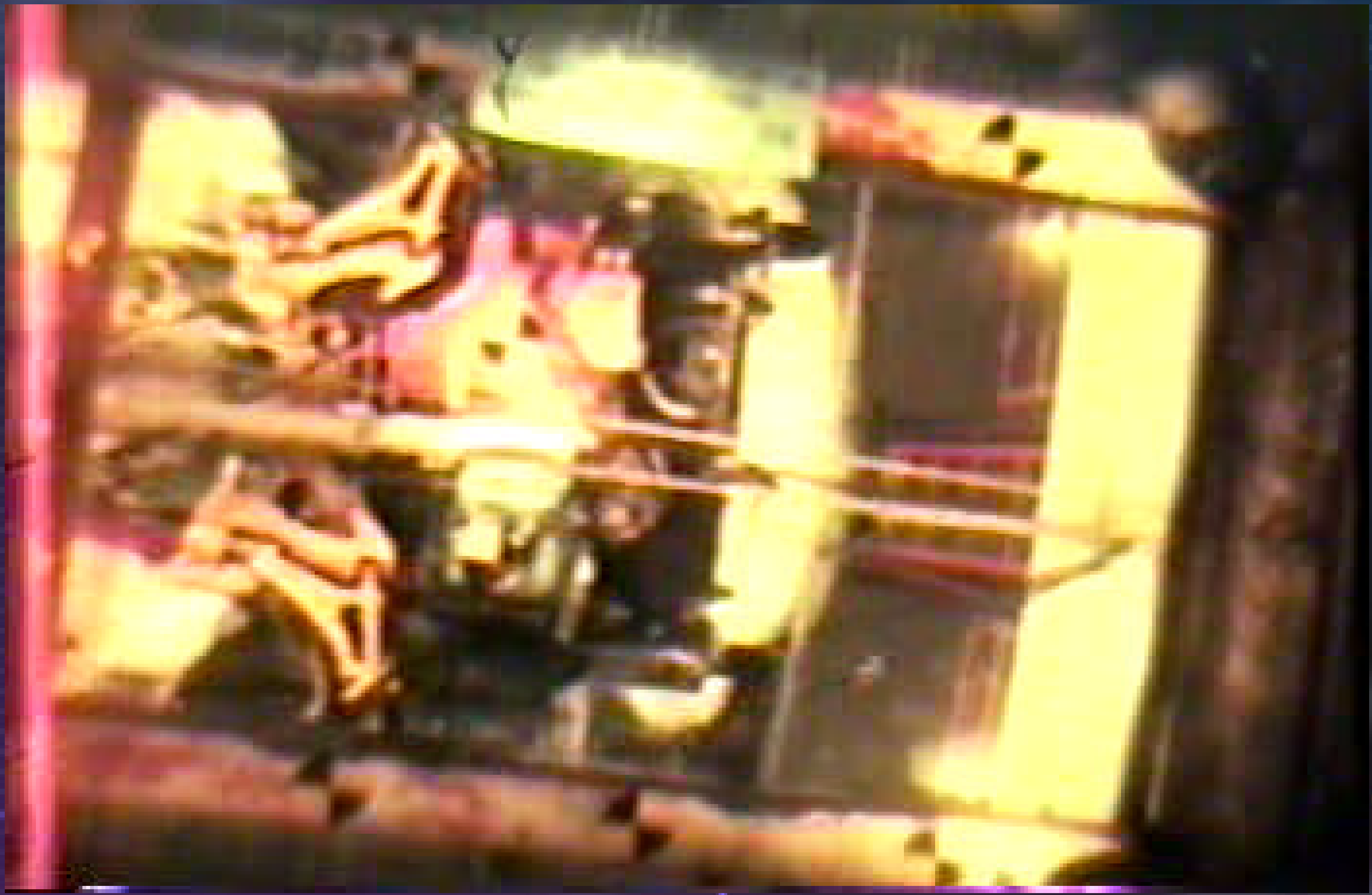


Belt Spool Out

NCAP

See Movie

NCAP Underside



See Movie

30 mph Compliance Test

NCAP and Compliance Tests
Other Applications

- Provide insights into dummy kinematics

- Provide insights into vehicle performance

- Compliance tests provide air bag response without belts

Input Data Needs for Crash Reconstruction

- Occupant Model
- Vehicle Interior Geometry
- Force Deformation, Friction and Hysteresis of Belts, Air Bag, and Other Contacts
- Crash Pulse (and Intrusion Time - Displacement)
- Initial Position of Occupant

Initial Position

- Driver Interviews
- Crash Investigation
  - Including Louie the Leg
- Trial & Error Modeling

Louie the Leg

Input Data Needs for Crash Reconstruction - Summary

- Occupant model
- Vehicle interior geometry
- Force deformation, friction and hysteresis of belts, air bag, and other contacts
- Crash pulse (and intrusion time - displacement)
- Initial position of occupant

What Lumped Mass Modeling Can Do

- Insight into occupant (dummy) kinematics
- Insight into injury mechanisms
- Sensitivity of crash parameters to modify injury risk
- Direction and approximate magnitude of applied forces

What FEM Models Can Do

- More accurately model human skeletal structure
- More accurately predict the joint forces that produce injury
- More accurately predict the stresses and strains that produce injury

Lower Limb Injury Criteria

- Upper Leg
- Lower Leg

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Femur Injury Allowable

Femur Force = 10000 N

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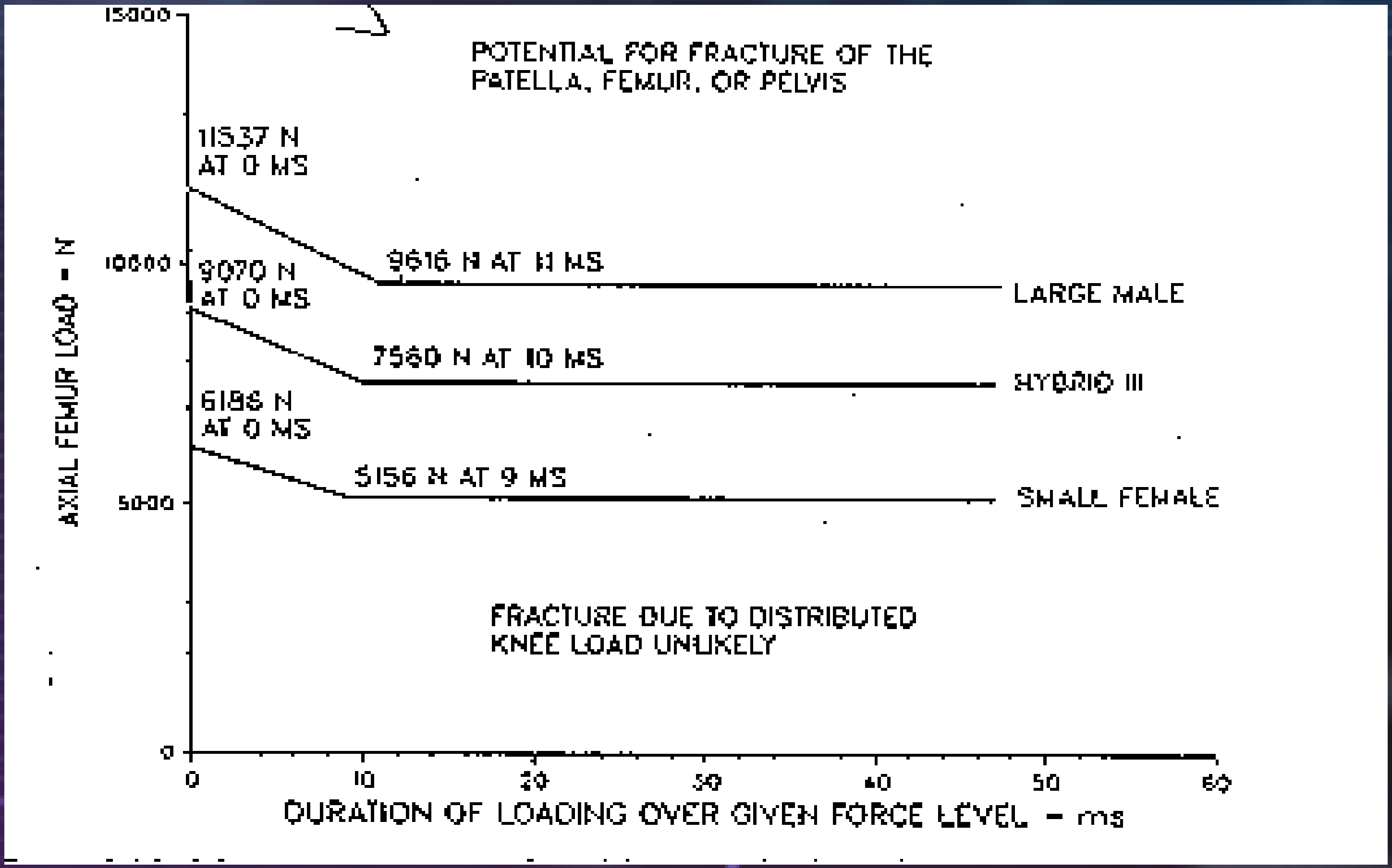
Injury Assessment Curves for Axial Compressive Femur Force Measured With Hybrid III-type Adult Dummies



Case 920027
Upper Leg Injury

Acetabulum Fracture-Dislocation

Why not a Femur Fracture?

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Case 92-027
Scene Diagram

Vehicle to barrier crash

Frontal impact

Construction zone, driving on wrong side of barriers

Clear, dry, dark

Delta-V = 30 mph

Crash Scene - Approach

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Crash Scene - Approach

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Crash Scene - Approach

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New 1992 Volvo

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Case Vehicle - 1992 Volvo

Use Damage to

Calculate

Crash Severity

Delta-V = 30 MPH

Case Vehicle - 1992 Volvo

- 1990 Volvo 740 GL
- PDOF 12 O'clock
- Delta V – 36.5 mph

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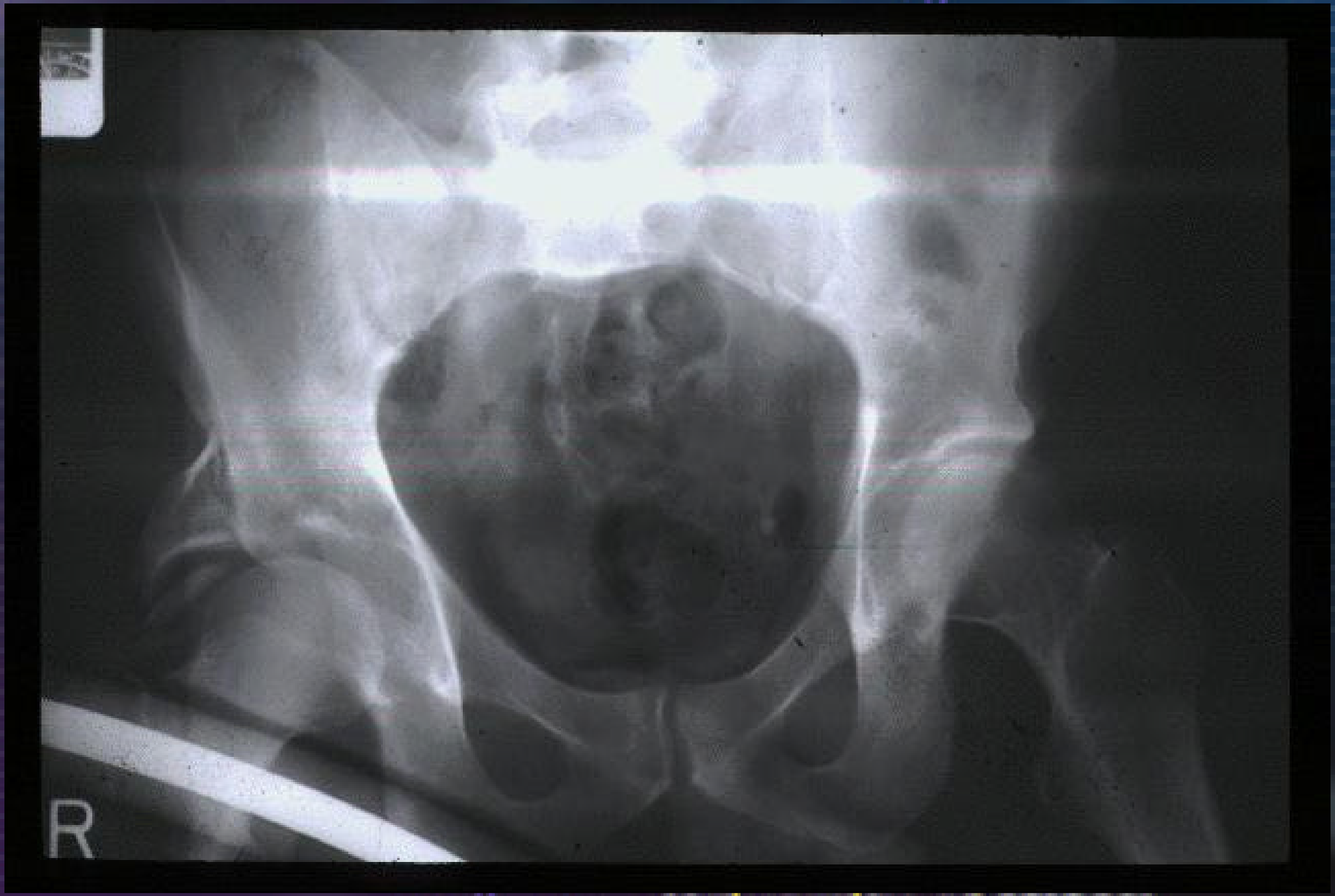
Driver

- 29 y/o male
- Firefighter
- 73” tall, 208 lbs.
- Air bag deployed
- Unbelted
- High suspicion criteria

Injury Overview

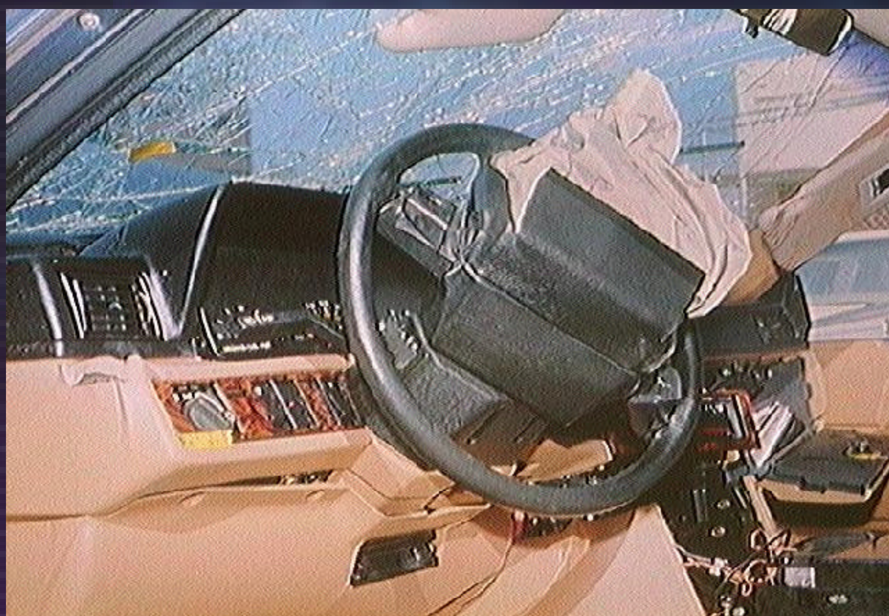
- Abrasions, Right Forearm, Flank - AIS 1
- Contusions, Right Forearm, Left Thigh – AIS 1
- Lacerations, Scalp, Right Forearm – AIS 1
- Fracture, Right Acetabulum – AIS 3
- Fractures, Left Ribs 5,6,7,8 – AIS 3

X-Ray of Principal Injury



Dislocation-
Head of
Right
Femur
AIS -3

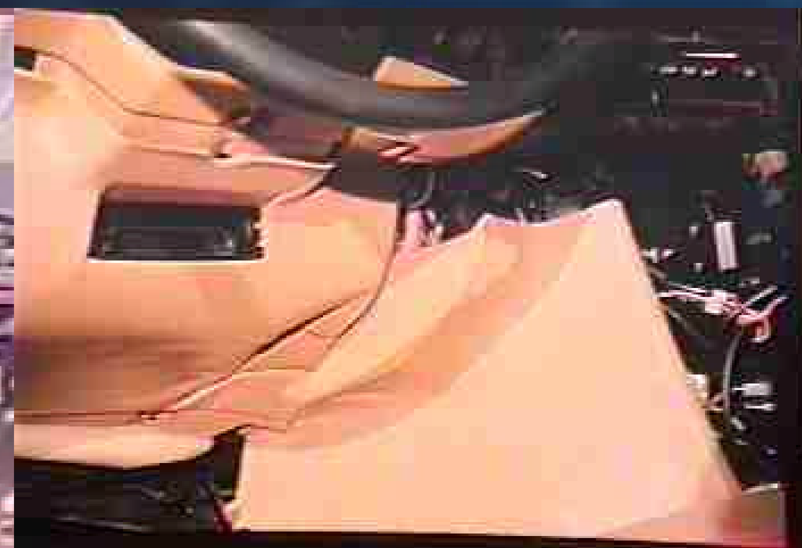
Case Vehicle Interior



- Steering wheel deformity – 4.5”
- Intrusions:
  - L Toe Pan – 4”
  - Center Console – 5”
  - L. floor – 4”

Vehicle Interior-
Air Bag Deployed

Vehicle Knee Panel



Location of Right Leg

Vehicle Knee Panel

Right Knee Contact with Knee Restraint

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What was the mechanism of rib fractures on left and head of femur dislocation on the right?

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Examine Same Vehicle in Government Test

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NCAP Test of 1991 Volvo

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Examine Similar Crash

Pole Crash with Ford LTD

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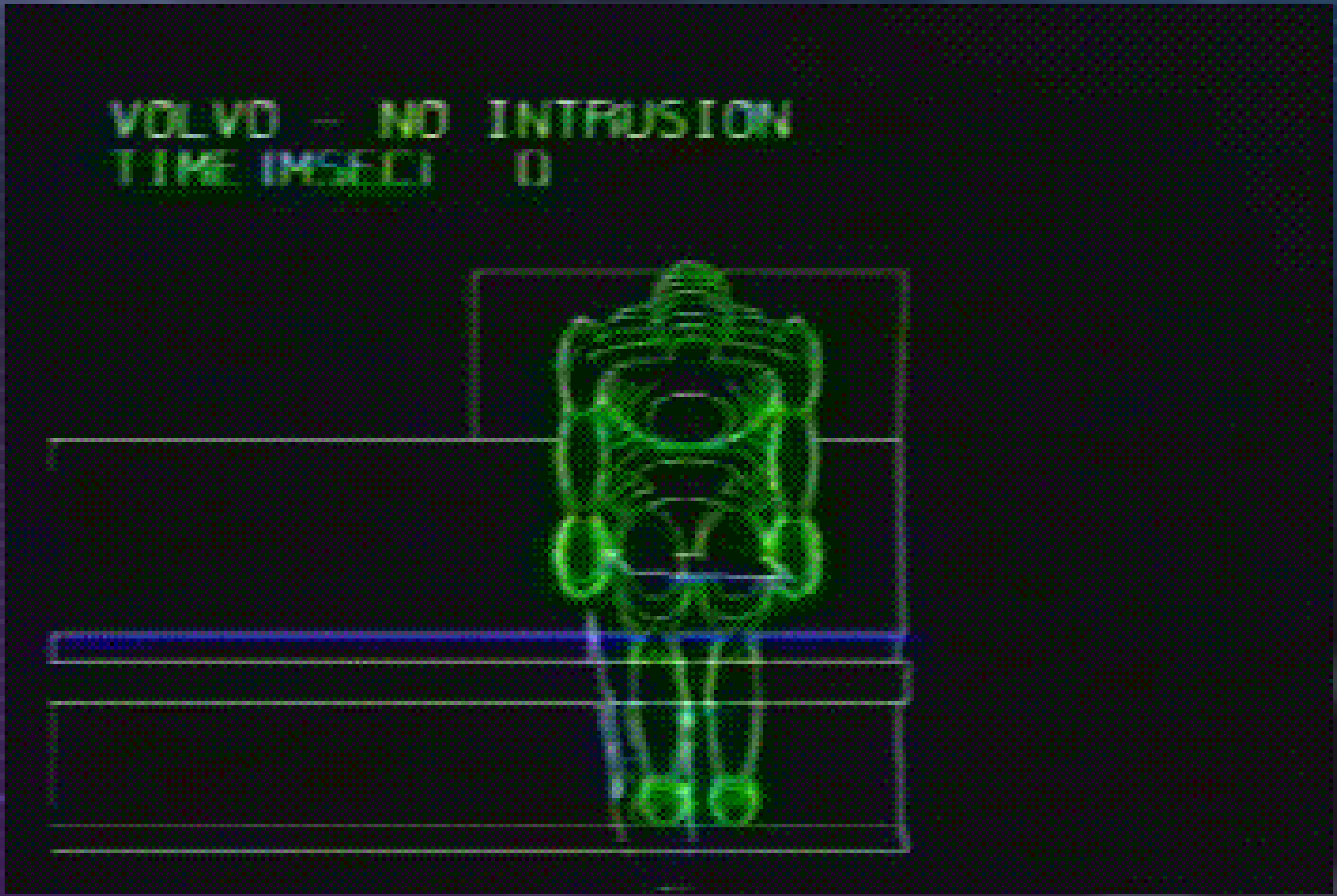
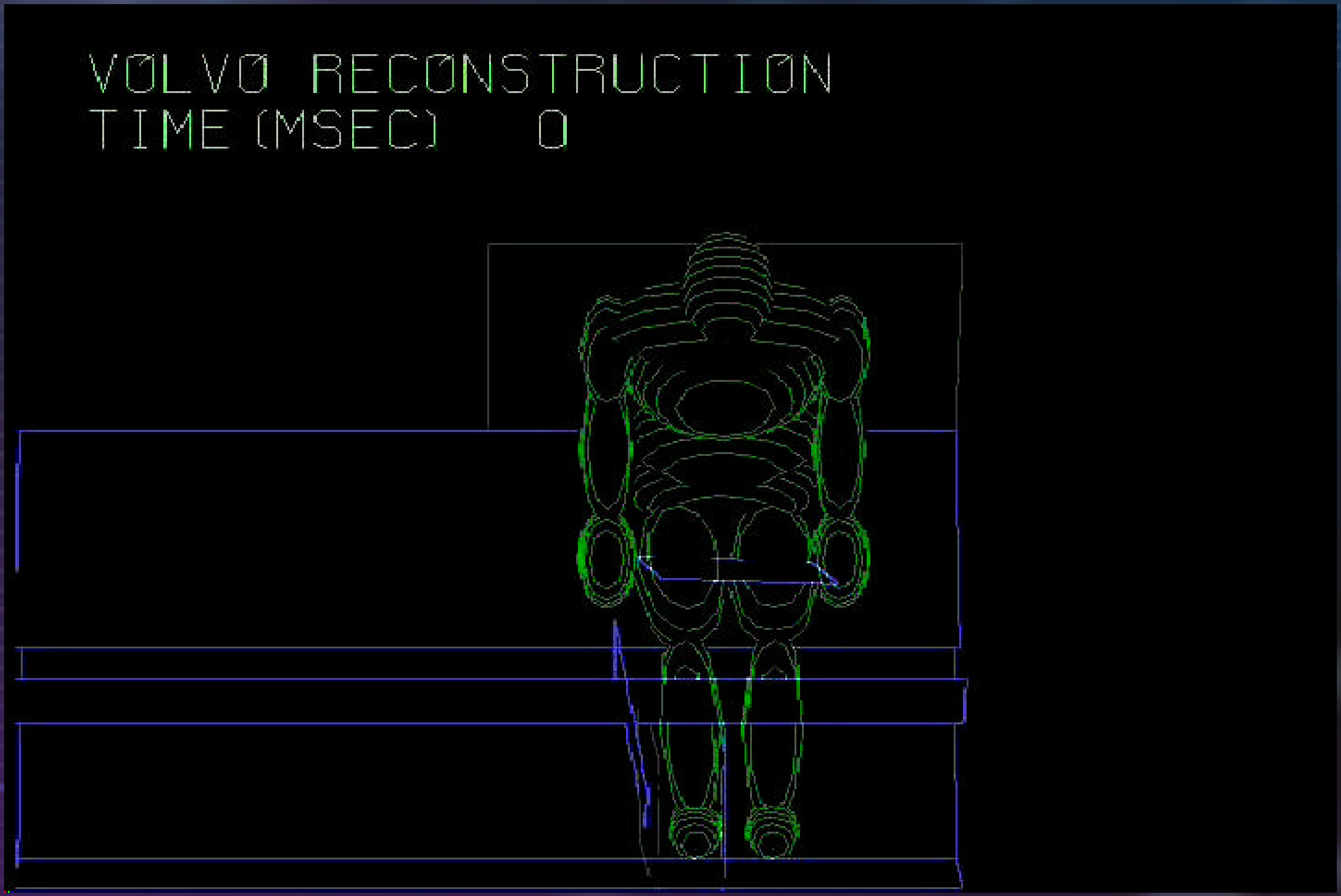
Ford LTD Into a Pole at 30 MPH

Reconstruction - No Intrusion

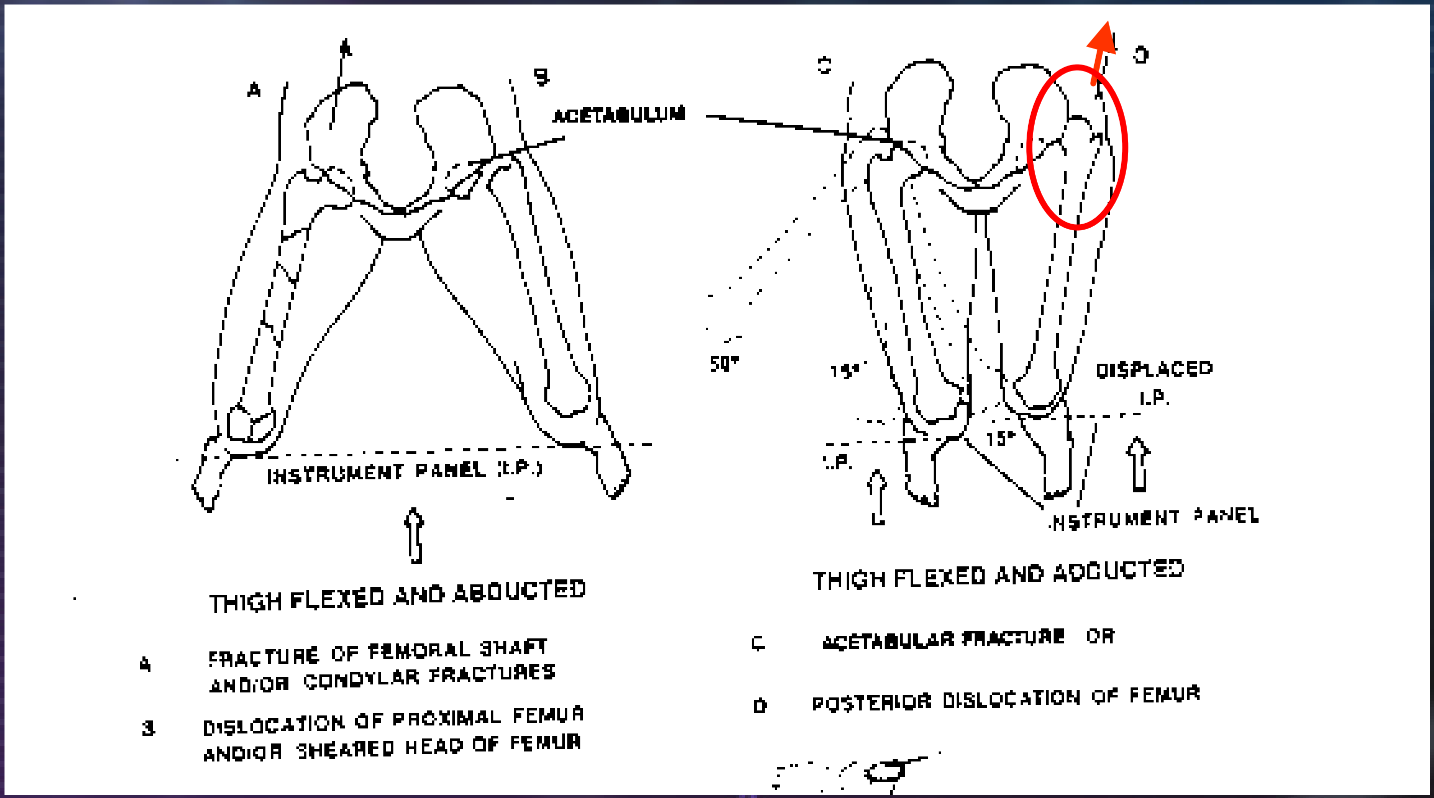


Applied Lump Mass Modeling

See Movie



Adducted Injury - Dislocation



Injury Mechanism

- Direct loading of chest
- Axial loading with external rotation of right hip

Hospital Data

- LOS – 17 days
- Operative procedure: ORIF of right acetabulum
- Hospital charges: $47,003.08
- Discharged home

Conclusions and Summary

- Air bag mitigated life threatening chest injuries.
- Knee protection good
- Lower extremity exposure to injury still high
- Adducted right leg increased vulnerability to dislocation

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Lower Leg Injuries (Below the Knee)

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Tibia Tolerance
Mertz Criteria

- Axial Compression (50th %) - 8000 N

- 5th % - 5104 N
- 95th% - 9840 N

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MECHANISMS OF FOOT/ANKLE INJURIES

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Ankle Injury Tolerance

Malleolar Fracture

- "The Role of Axial Loading in Malleolar Fracture", Funk, Tourret, George, and Crandall, SAE 2000-01-0155
- Produced malleolar fracture from axial impacts of cadaver feet with 16 cm of intrusion
- Varied initial foot position
- Observed subsequent inversion or eversion
- Results ----

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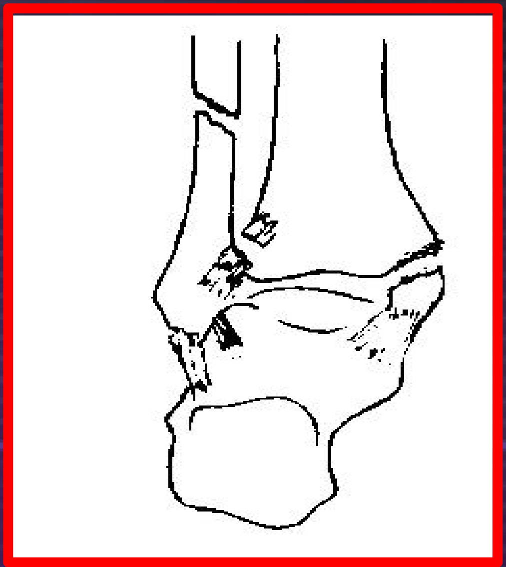
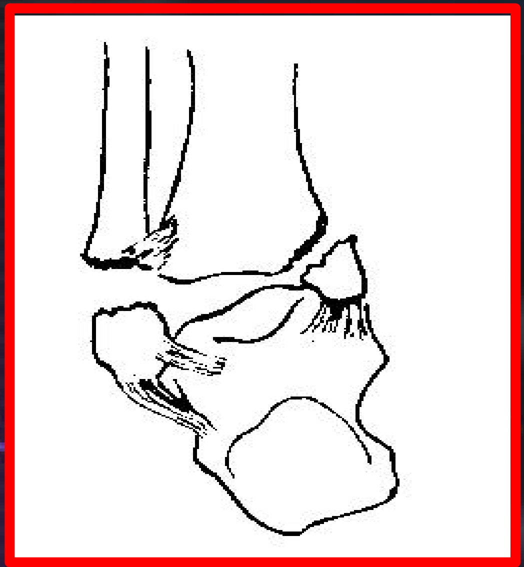
Cadaver Test Results

Initial Position	Direction of Bending	Location of Fracture	Force at Fracture
10^{o} Inversion	**Inversion**	**Lateral**	**5473N**
30^{o} Pf	**Eversion**	**Medial**	**7929N**
Neutral	**Eversion**	**Medial**	**7349N**

Eversion



Inversion



Case Presentation

Lower Leg Injuries
(Below the Knee)

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Case 93-020
Scene Diagram

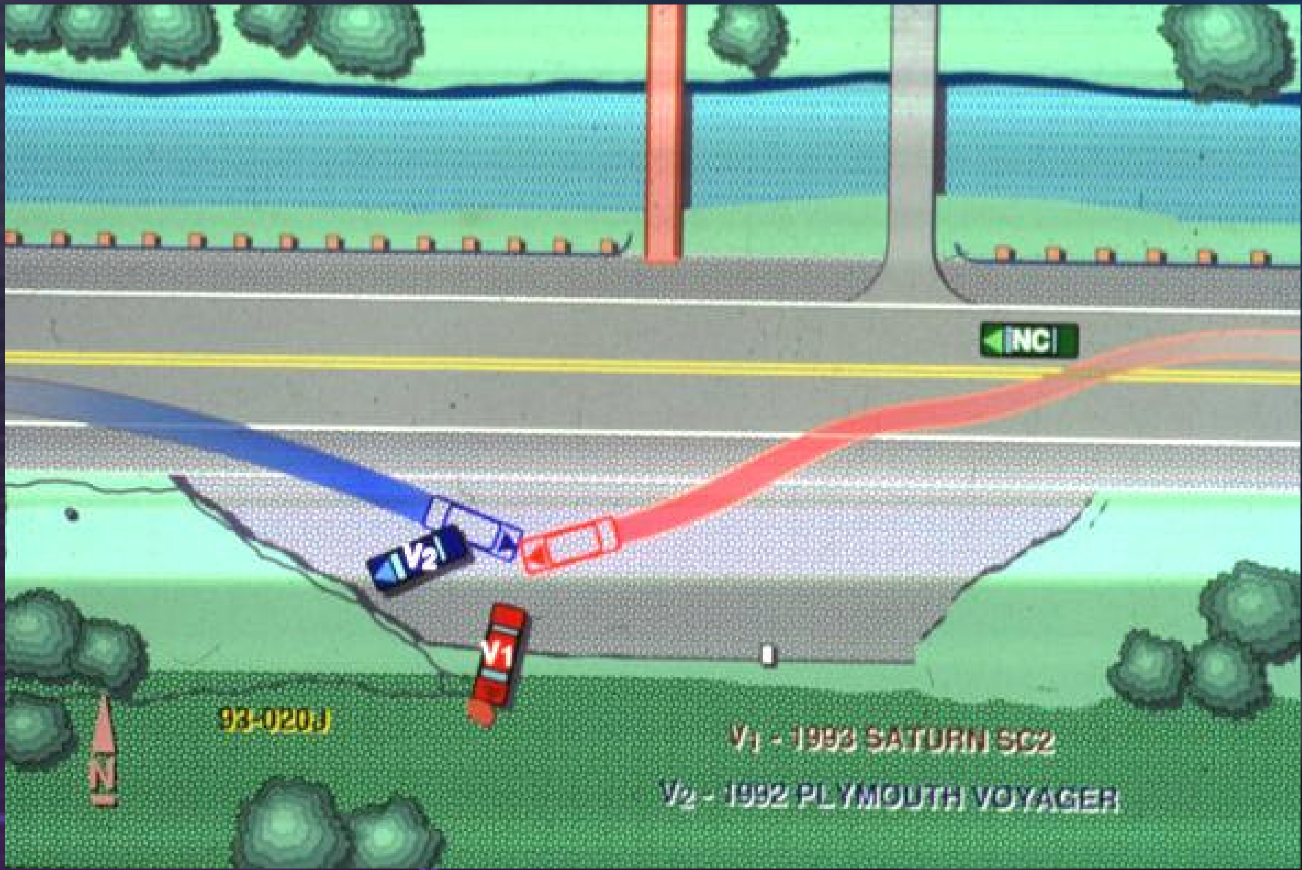
Car-to-Car Crash

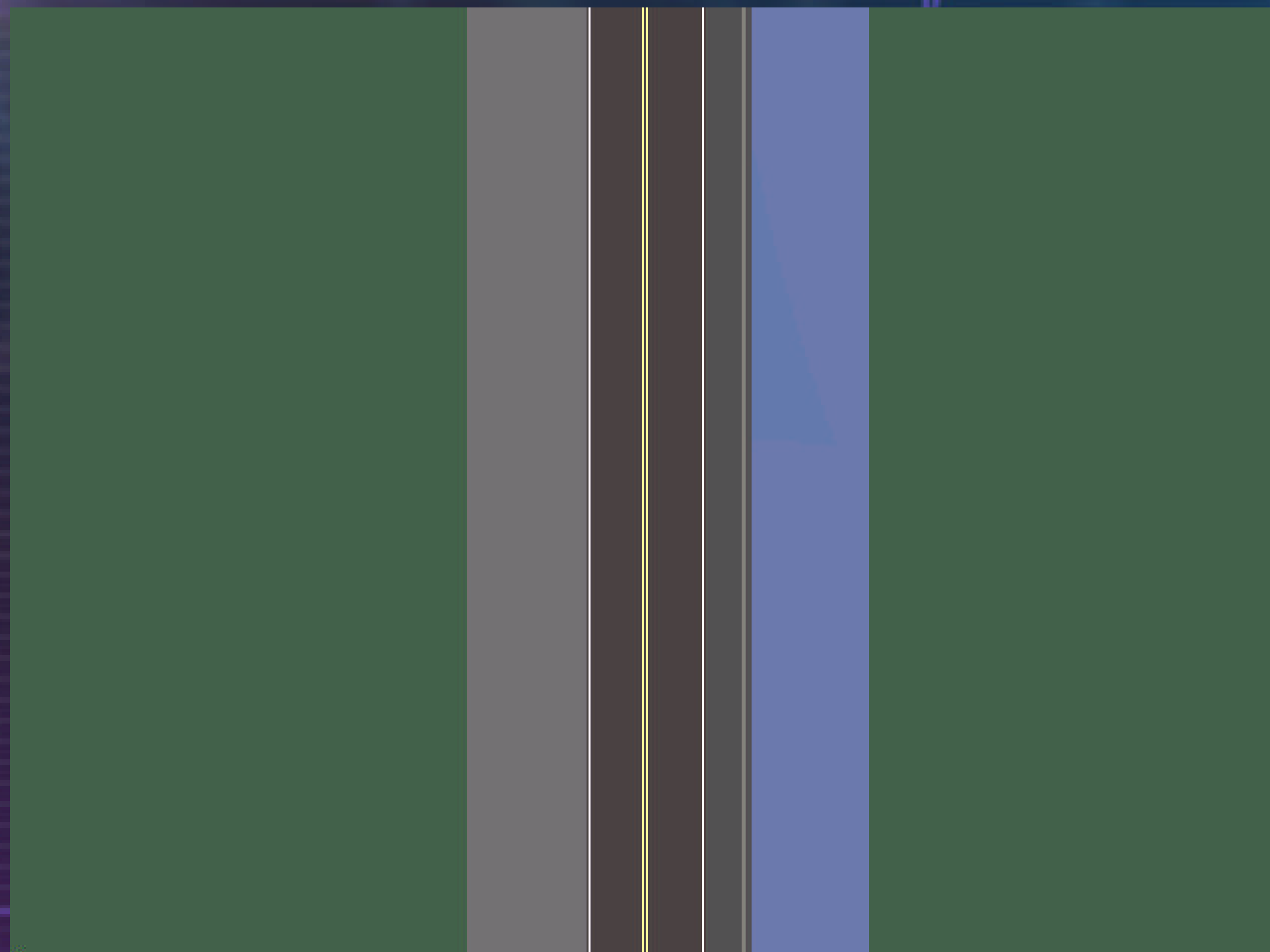
Frontal Offset

Rural 2-Lane Road

Clear, Daylight

Passing Maneuver





See Movie

Case Vehicle

Frontal Offset
1 O'clock
20^{o} Oblique
DeltaV- 32 mph
1993 Saturn SC2

POV - Plymouth
Minivan (1992)

Case Vehicle

1” of Left Toe Pan Intrusion

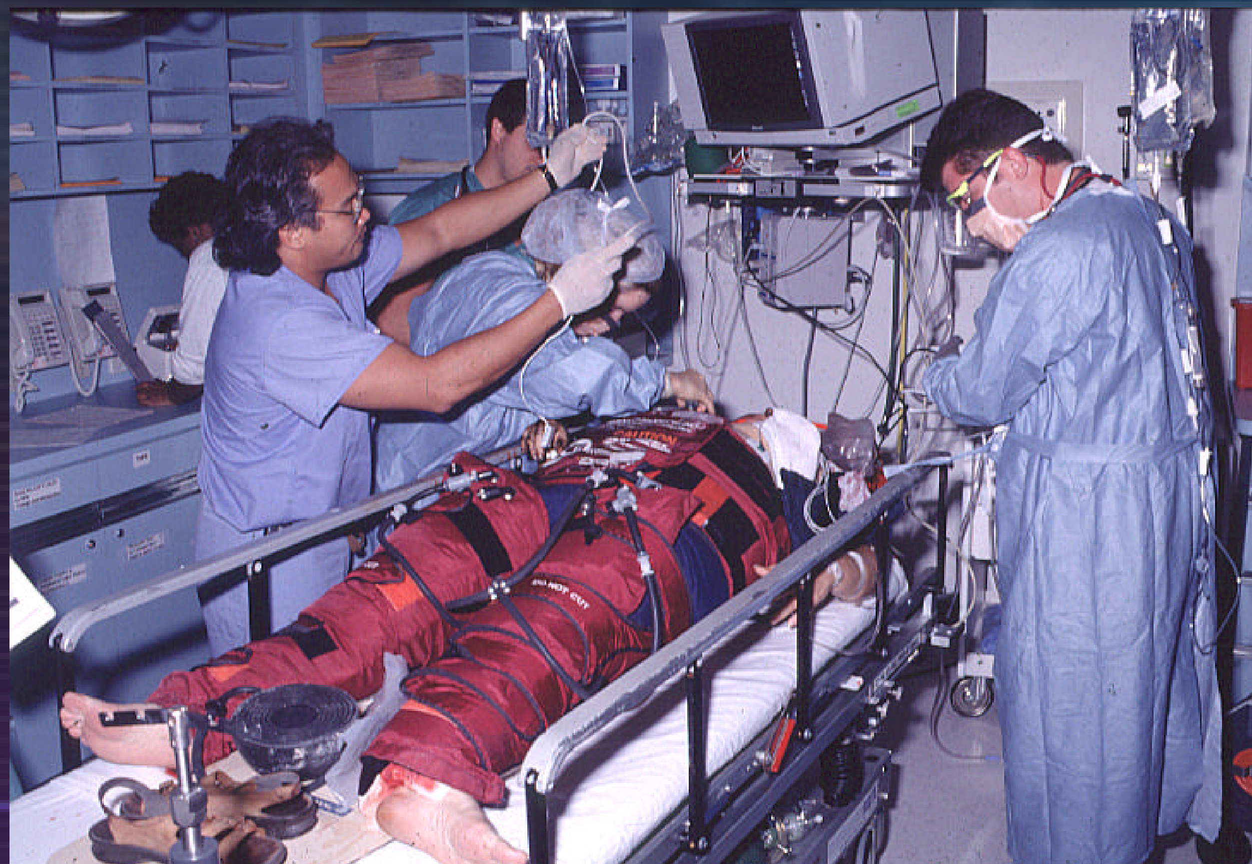
Vehicle Interior

Steering Wheel Removed by Rescue Squad

Case Vehicle Driver

53 YO Female
5’2”; 205 lbs.

Did not meet
trauma criteria



Driver Injuries

Liver Lac - AIS 2

Rib Fx - AIS 2

Tear, Renal Artery AIS-3

Burn Right Arm - AIS-2

Open Fx R. Ankle - AIS-2

Open Fx. L Ankle - AIS-2

Driver Injuries

Liver Lac - AIS 2

Rib Fx - AIS 2

Tear, Renal Artery AIS-3

Burn Right Arm - AIS-2

Open Fx R. Ankle - AIS-2

Open Fx. L Ankle - AIS-2

Chest Injuries

Liver Laceration - AIS 2

Rib Fracture - AIS 2

Apply Lumped Mass Model -
1 - Examine Chest Loading by 2-Point Belt
2 - Examine the Loading of Lower Limb Injuries

Computer Reconstruction of Occupant Loading

- Input Vehicle Acceleration
- Model Occupant Using ATBModel
  - Lumped Mass Model (Like MADYMO)
- Model With Air Bag & Without Intrusion
- Add Intrusion
- Retain Air Bag Forces, but Remove it Graphically to Show Driver Kinematics

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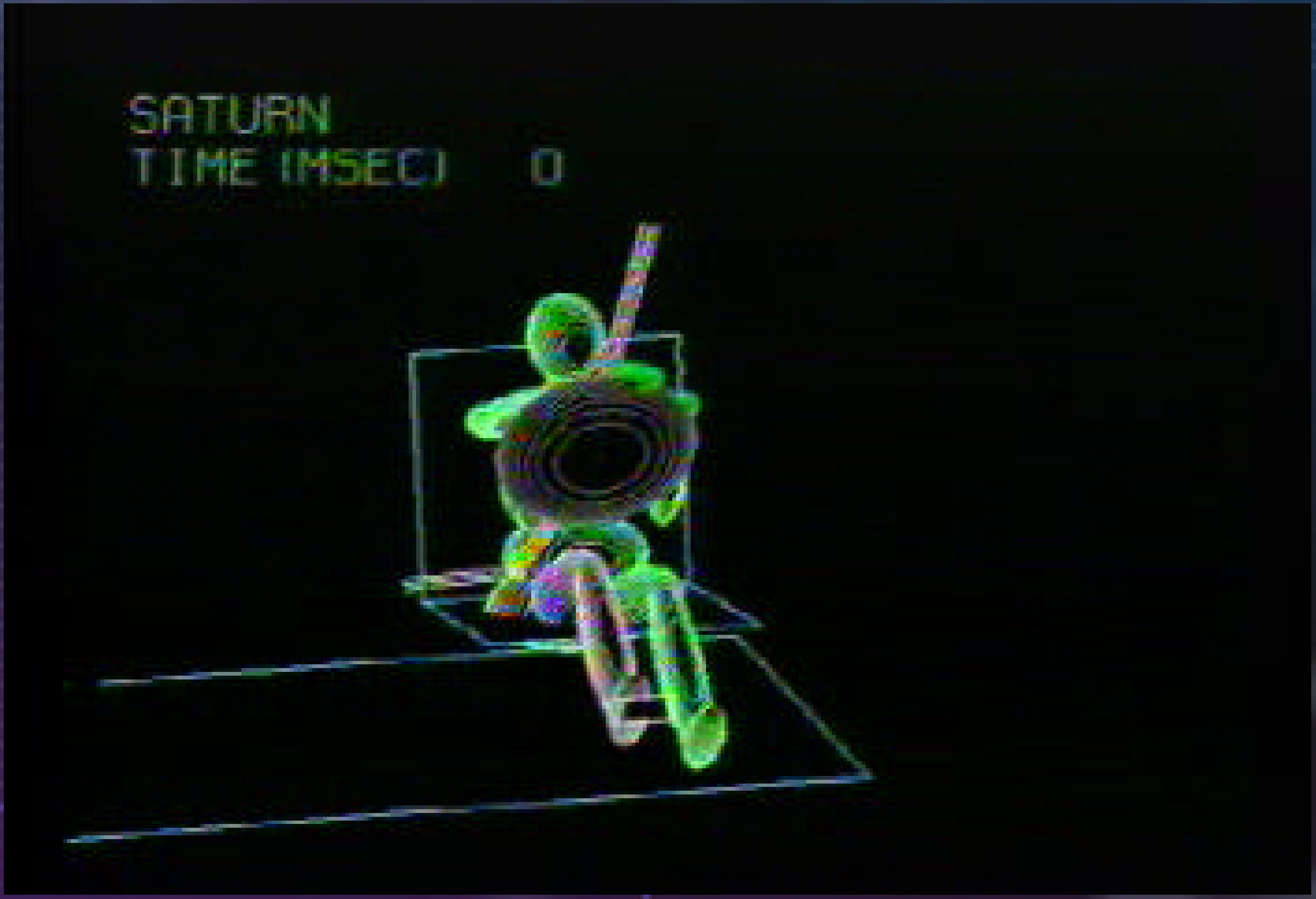
Occupant Motion -Lower Limbs

See Movie



Right Ankle Injuries

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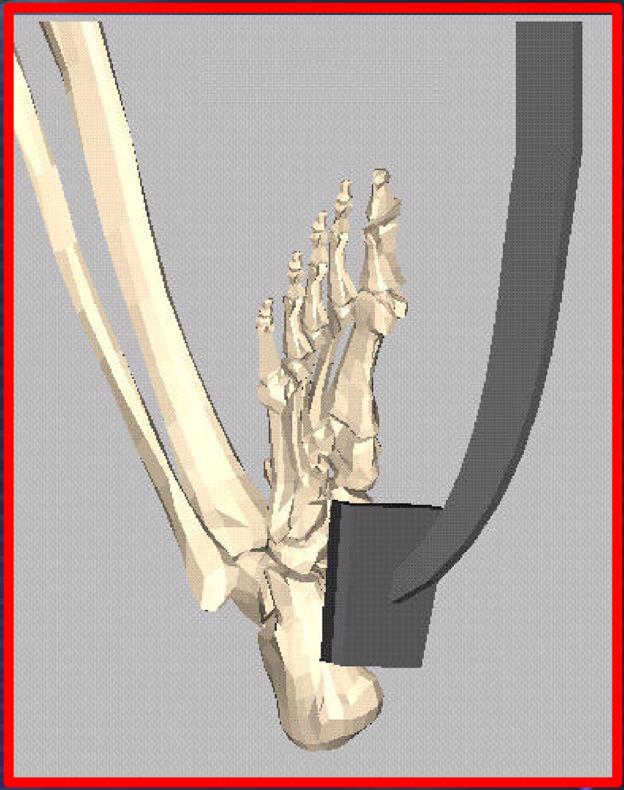
Right Ankle Injuries



Right -Open Pilon Fracture
Dorsiflexion Mode

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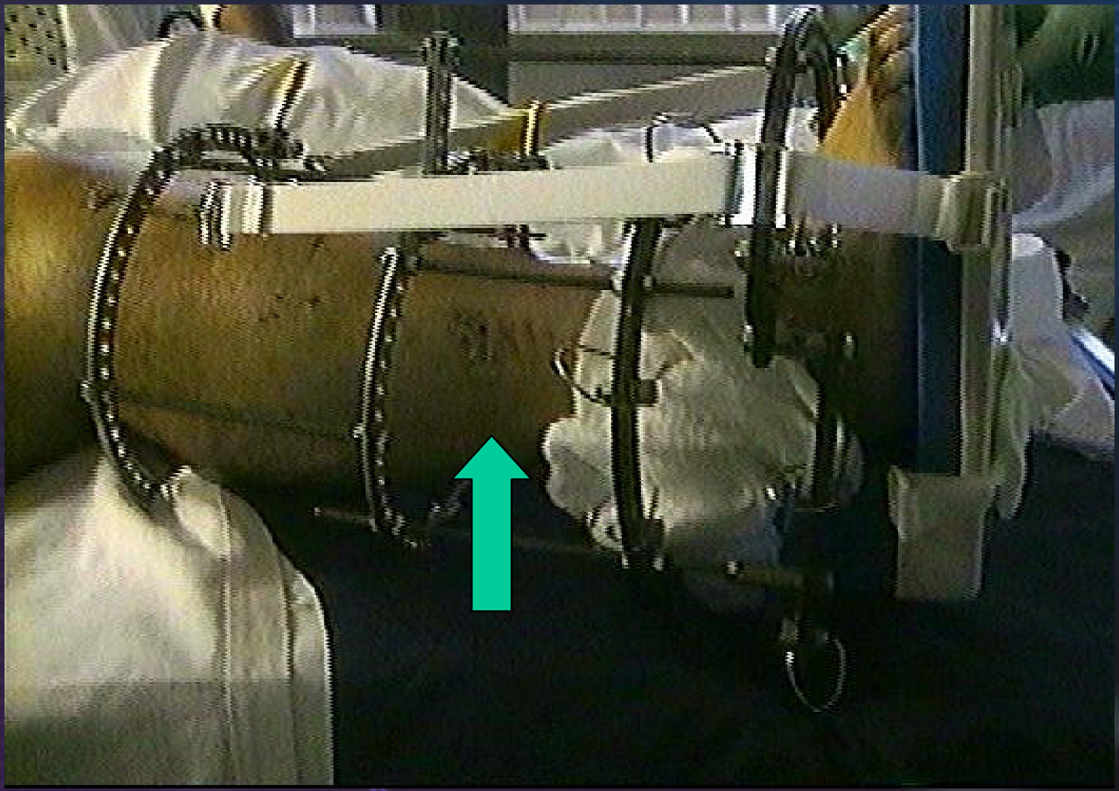
Vehicle Brake Pedal Deformation

2” Lateral Shift

1” Toepan Intrusion

Right Leg Abrasions



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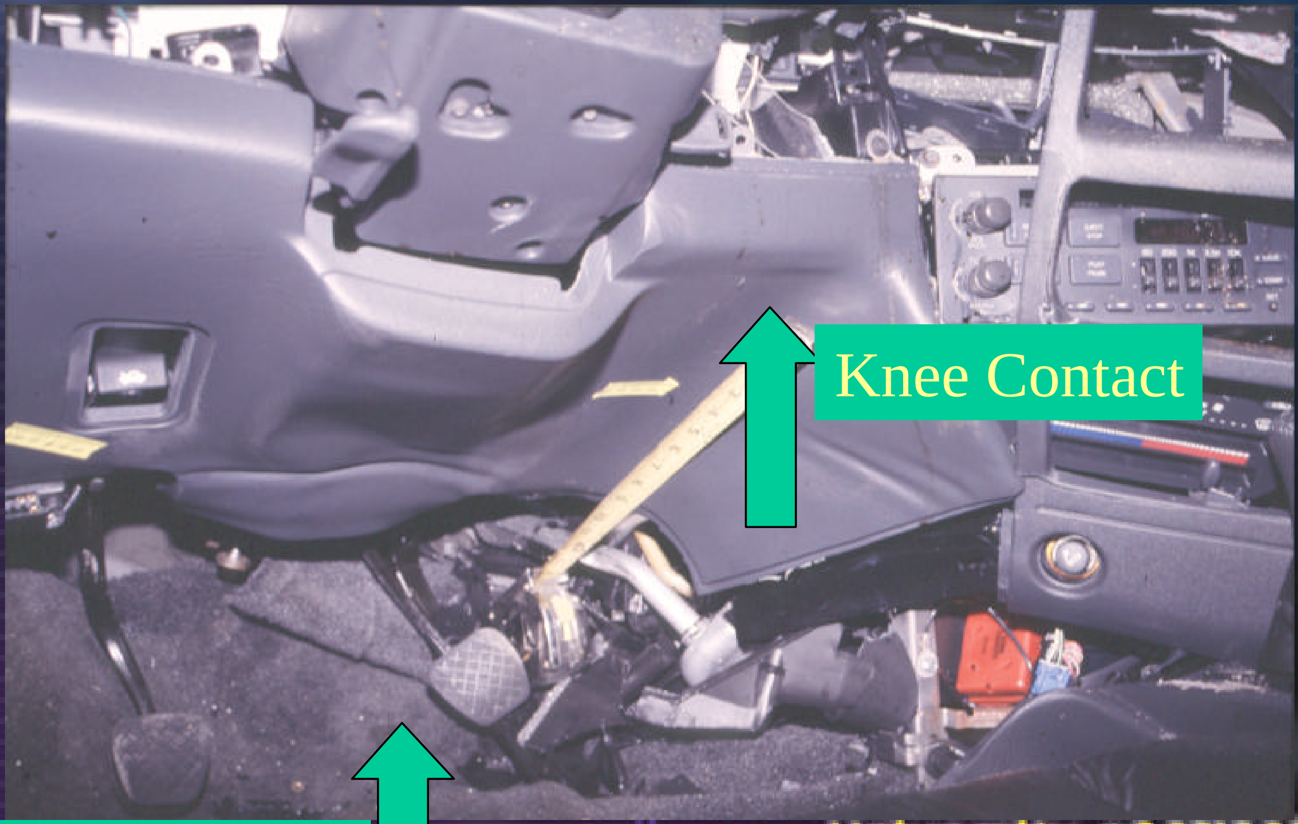
Abrasion Source

Locating Lower Limbs

Position of Right Foot

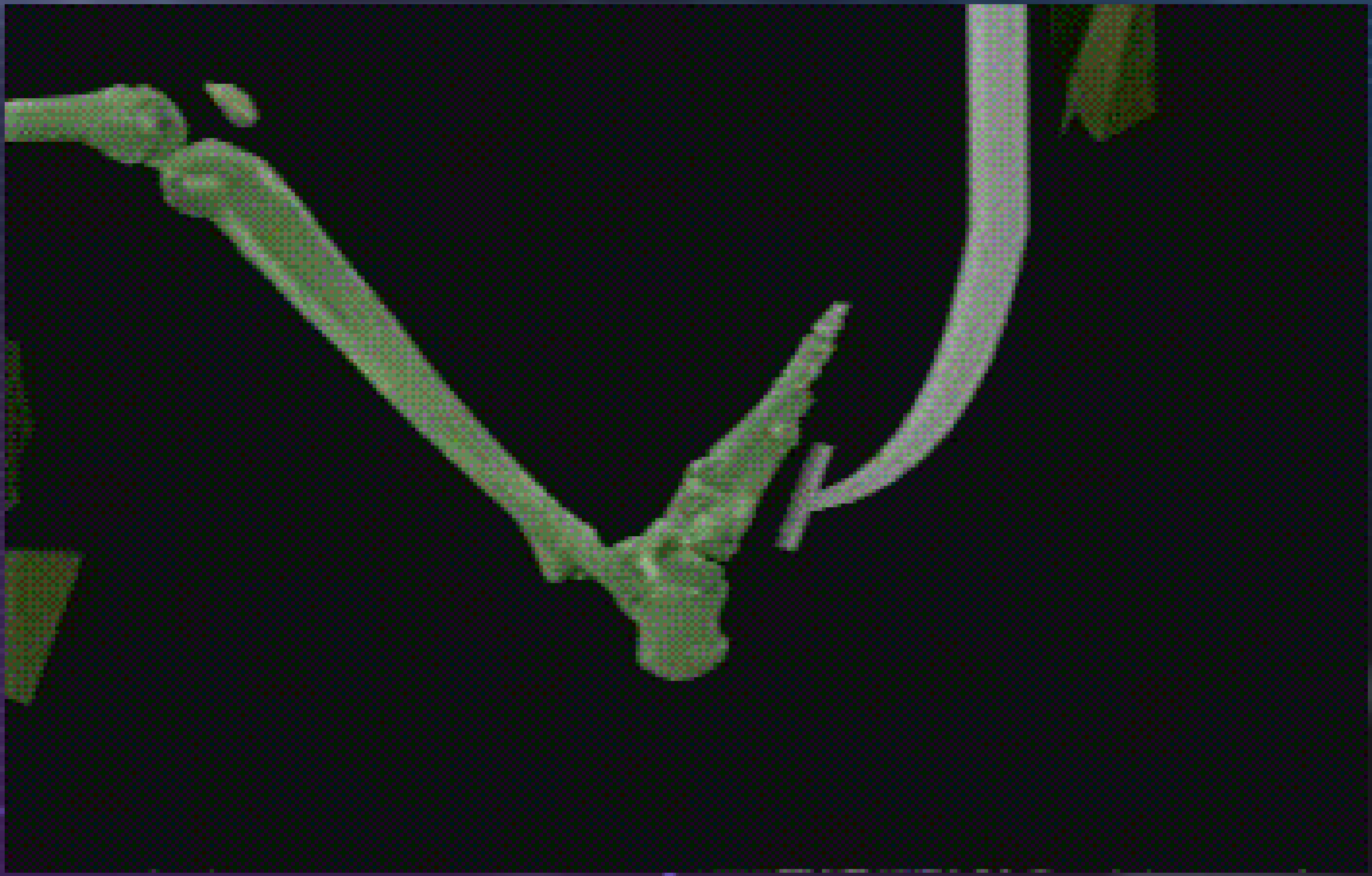
Right Limb Contacts



Evidence of Bracing

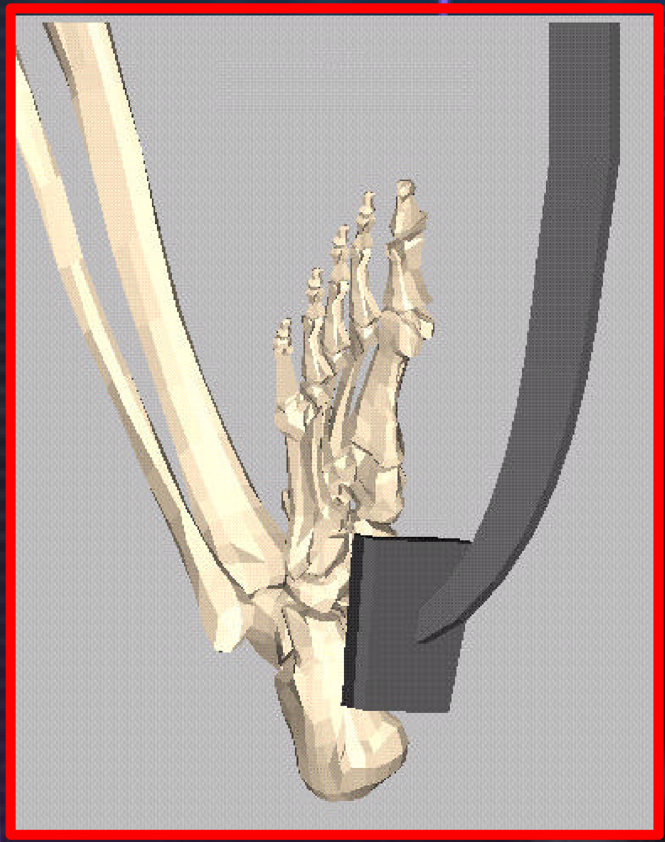
Right Foot Simulation

See Movie



Case Simulation Results

Right Ankle Injury Caused by Severe Bracing and Brake Pedal Loading



Right - 48^{o} dorsiflexion
Tibia force = 11.2 kN

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Left Ankle Injury

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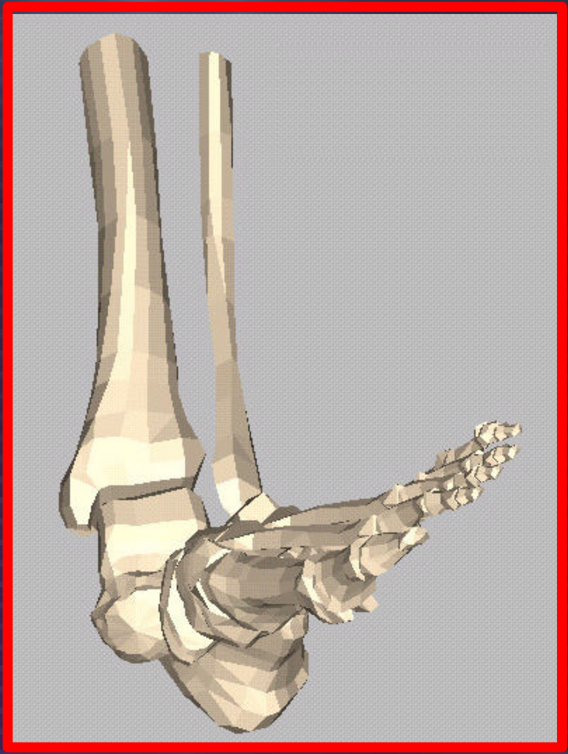
Left Ankle Injury



Left - Open Fracture/dislocation
Talo-Calcaneo-navicilar Joint
Eversion Mode

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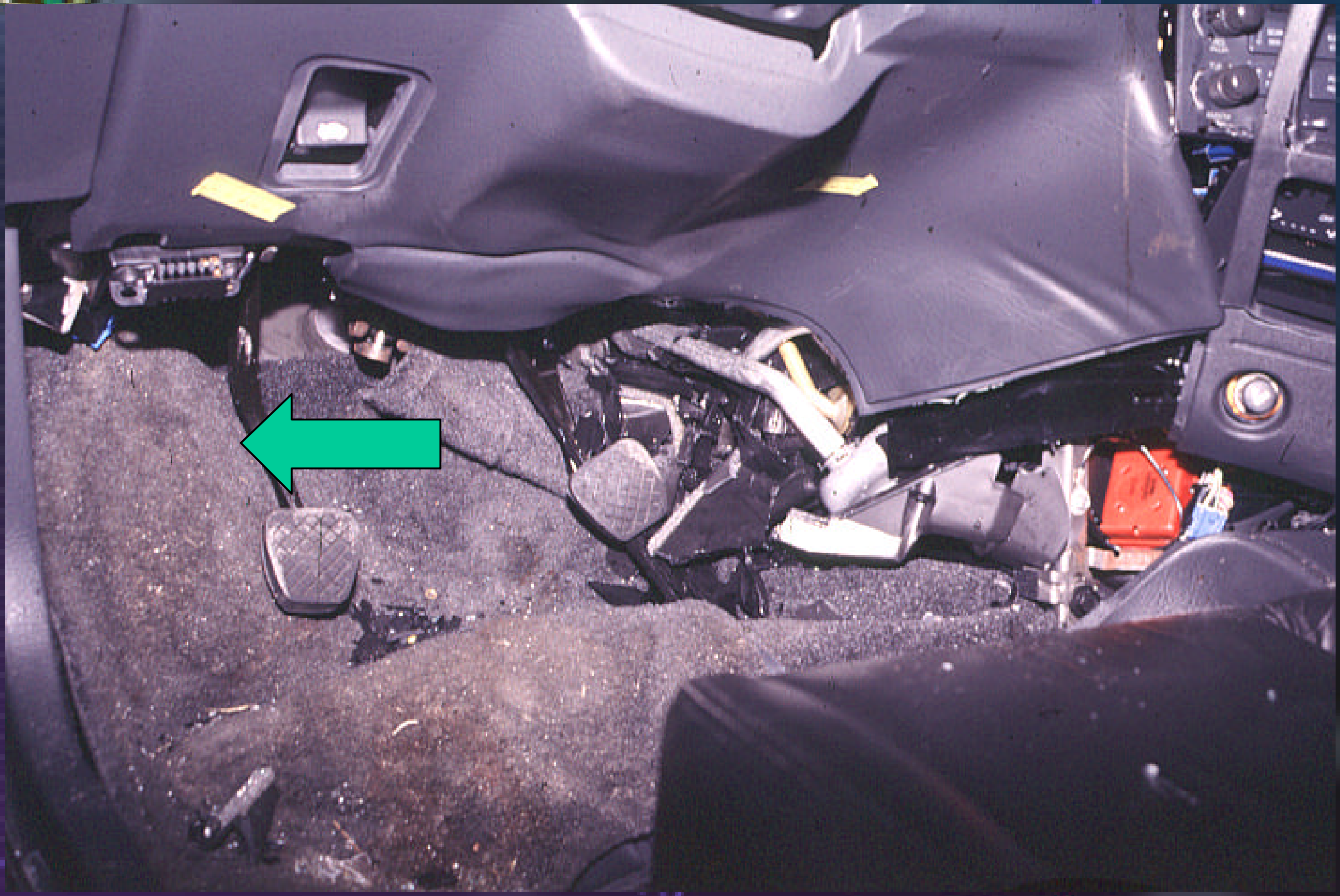
Eversion injury with minor toepan intrusion?



Apply Crash Tests & Modeling to Answer the Question

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Offset Crash Tests from NHTSA & IIHS Files

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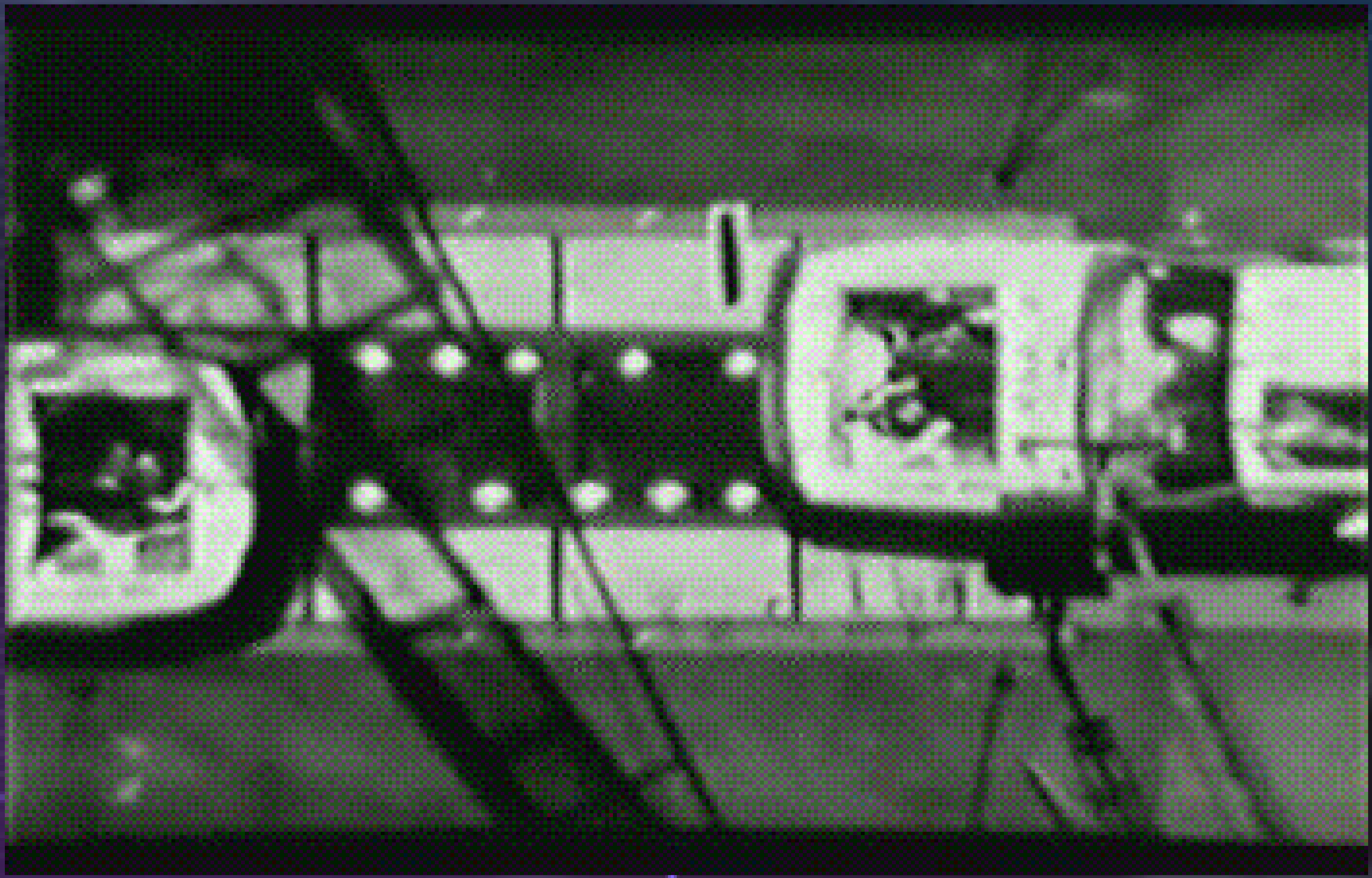
See Movie

Force Vector in Car-to-Car Offset Crash

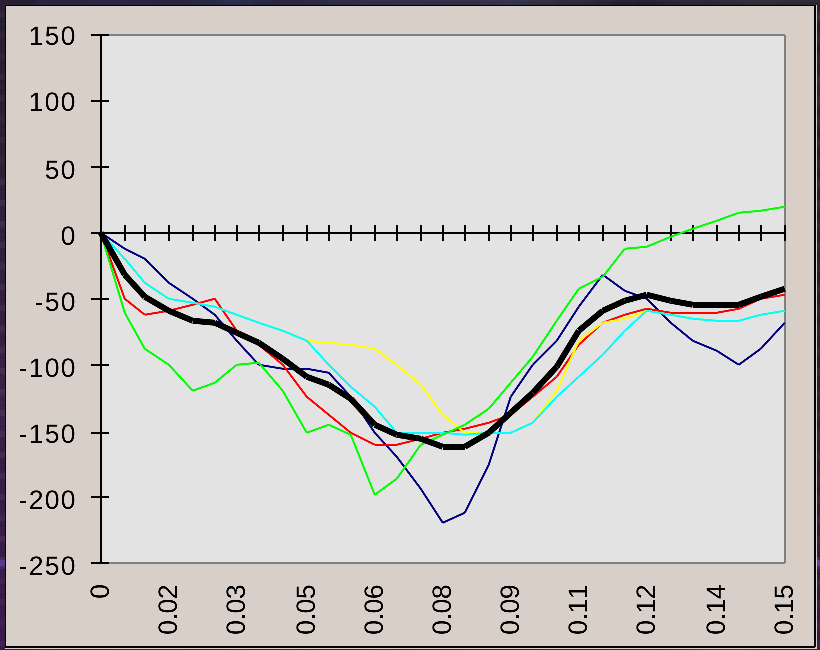


Crash Pulse Determination

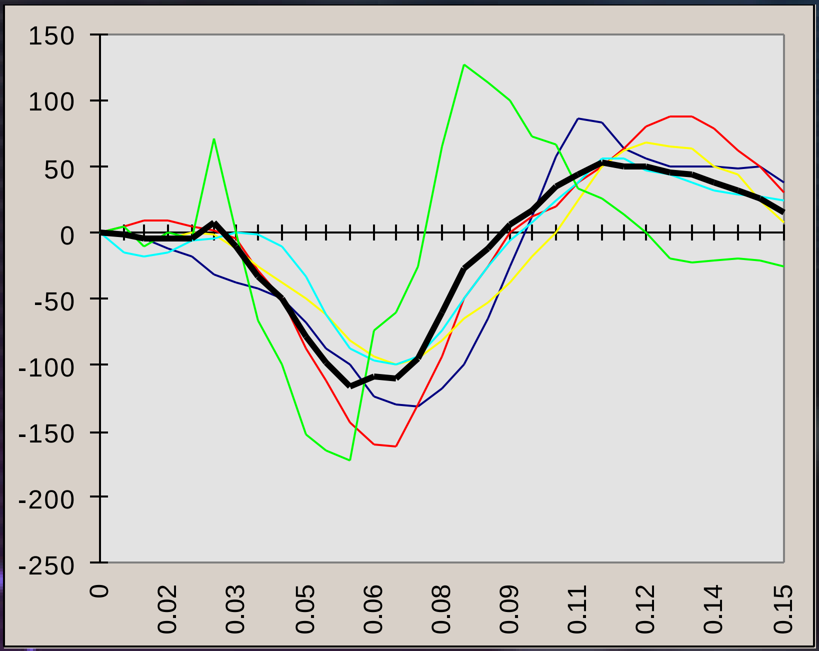
Car-to-Car Offset Frontal

Crash Accelerations

Longitudinal Pulse

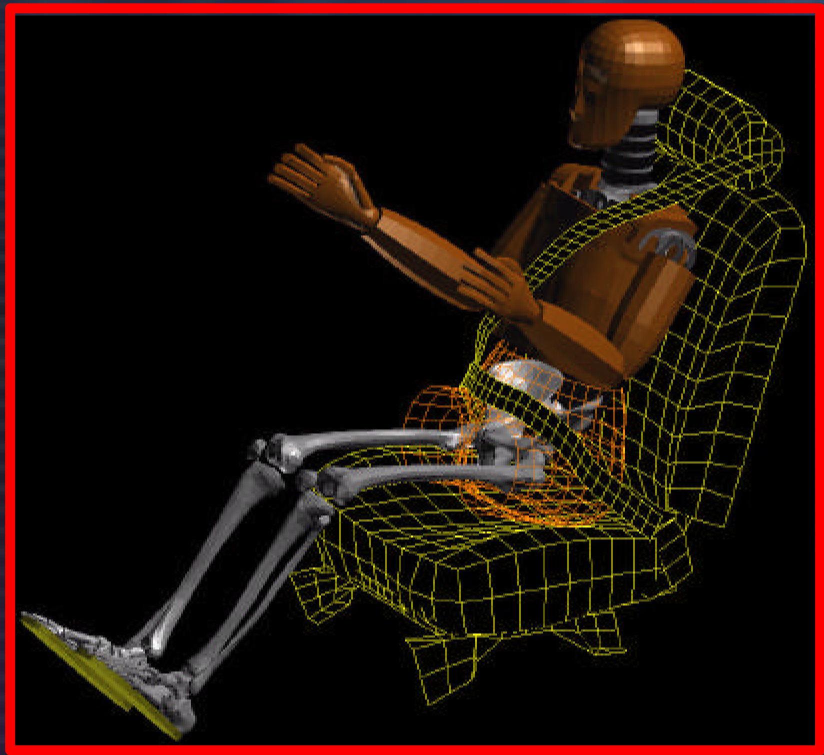


Lateral Pulse



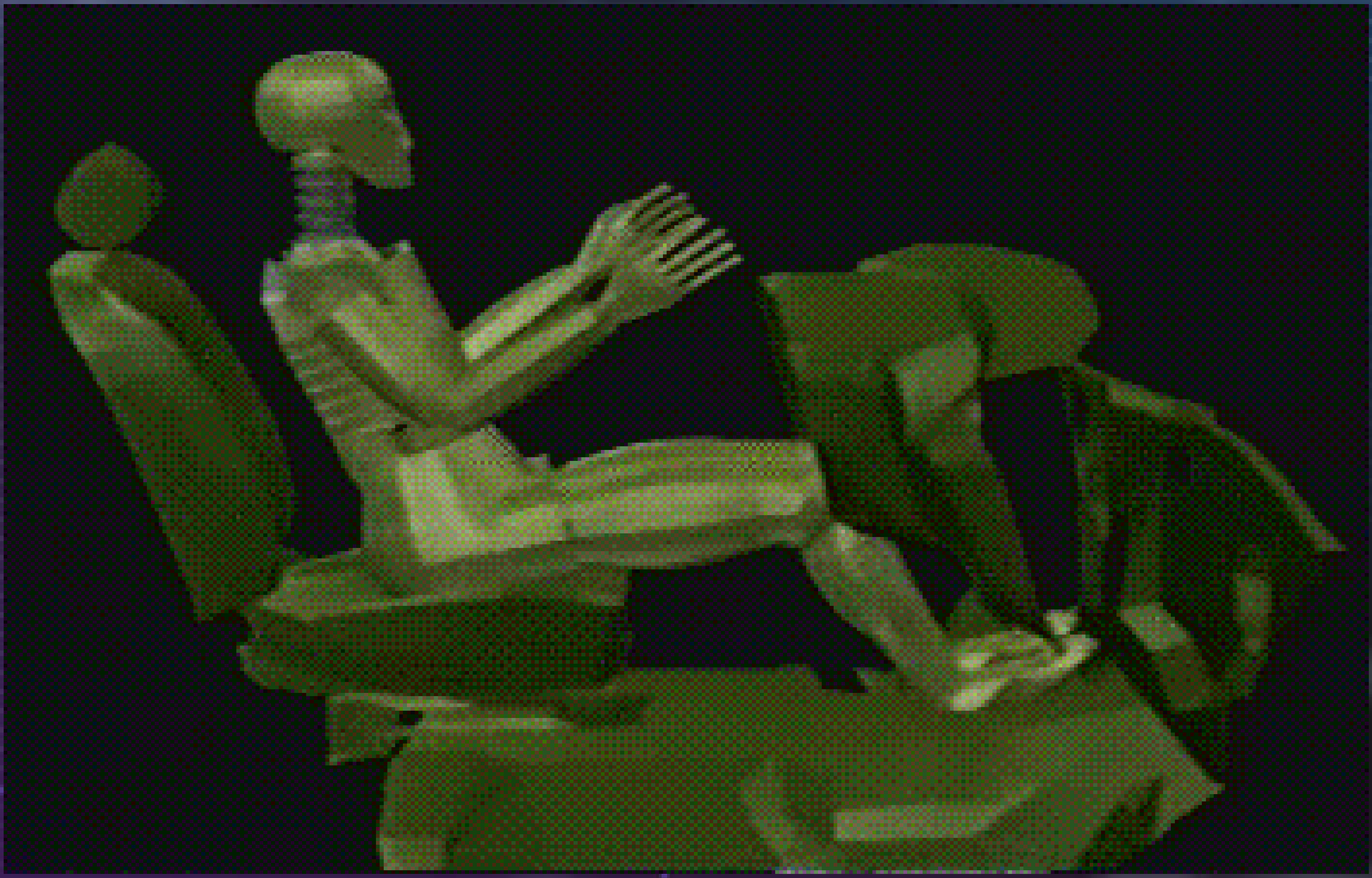
Computer F-E Model of Human Lower Limbs

- FEM Model of Dummy
- Validation
- FEM Model of Human Limbs
- Validation
- Combine Models
- Apply to Injury Mechanisms



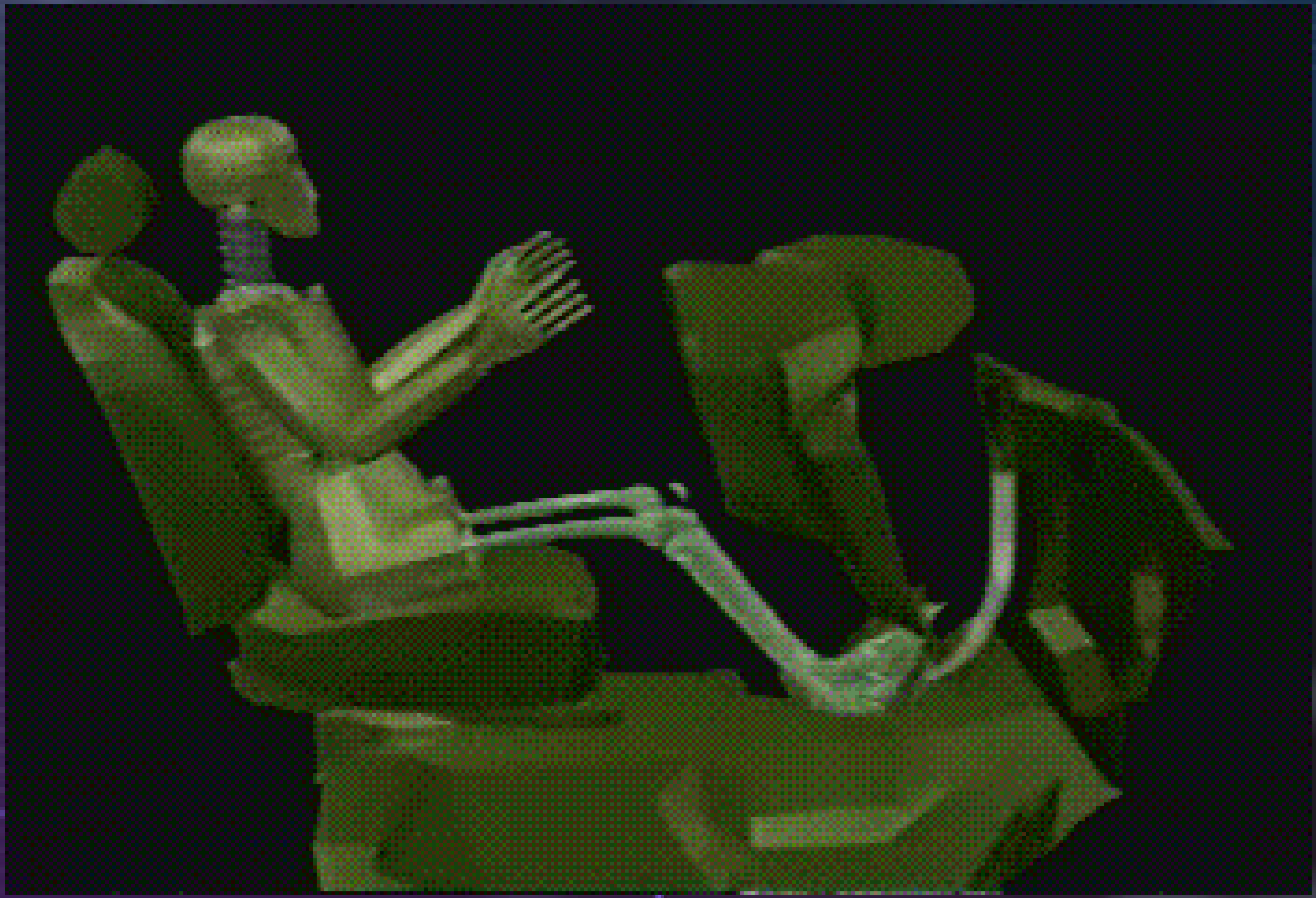
Dummy/Leg FEM Model in Frontal Offset Crash

See Movie



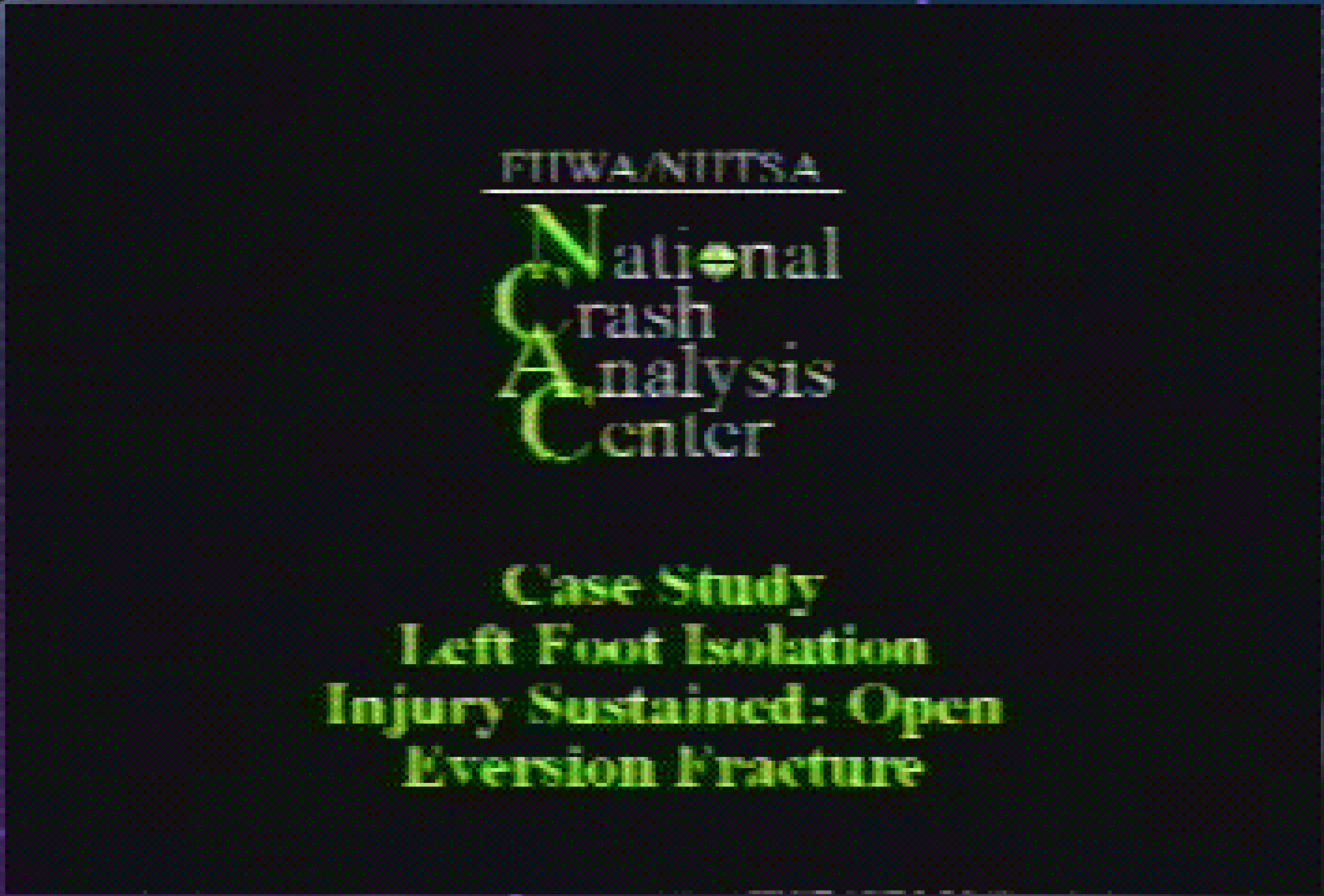
Dummy/Leg FEM Model in Frontal Offset Crash

See Movie

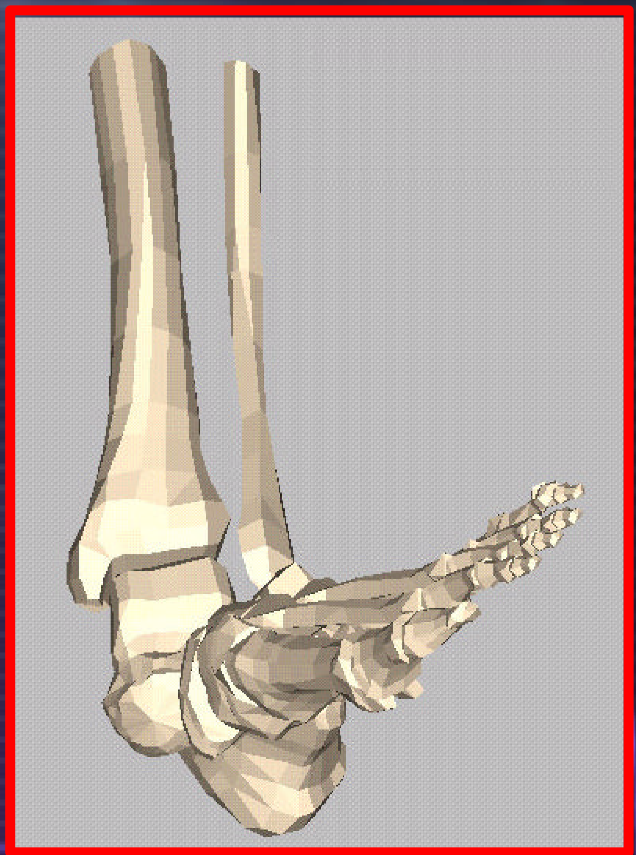


See Movie

Left Foot Simulation



Case Simulation Results



Left ankle - Eversion
- High axial load
- Crash pulse with lateral component
- Uneven floor

Tibia force = 8.6 kN
Left - 53° Eversion

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Summary of Injuries & Causes

- Right ankle - dorseflexion from braking
- Left ankle - eversion from axial load, lateral component in crash pulse, & uneven floor
- Liver - shoulder belt loading
- Abdominal aorta - bracing

Principal Findings

- Shoulder belts w/o lap belts induce liver injuries
- Eversion injuries are possible without significant toepan intrusion
- Lateral acceleration acts to increase vulnerability of ankle joint to inversion/eversion

Conclusions

- Crash reconstruction improves understanding of injury mechanisms
- Application of crash tests and analysis aid in understanding injuries
- Eversion injuries can occur with no intrusion
  - High Axial Load
  - Lateral Acceleration
  - Uneven floor

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